RADIATIVE FORCING PROTOCOL

Methods and Applications

Developed in alignment with the IPCC Fifth and Sixth Assessment Reports

VERSION 2.0 (2026)

Radiative Forcing Protocol: Methods and Applications

Version 2.0 (2026)

Published for General Usage

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Foreword

The Radiative Forcing (RF) Protocol is intended to support market applications of climate science and methods summarized in IPCC reports beginning in the First Assessment Report and updated in subsequent reports, most notably the IPCC AR5 *Climate Change 2013: The Physical Science Basis*; IPCC SR1.5 *Global Warming of 1.5°*, and IPCC AR6 *Climate Change 2021: The Physical Science Basis*. The RF Protocol framework was developed and refined over more than a decade by SCS Global Services and its partners.

The RF Protocol is the first climate accounting framework designed to comprehensively evaluate the radiative forcing reduction potential of projects by considering all emission and non-emission climate forcers, both positive and negative, over multiple timeframes of analysis. The purpose is to identify climate mitigation activities that can be readily deployed to rapidly slow, and ultimately reverse, the rise in excess radiative forcing that is destabilizing our climate.

Scientific Certification Systems, Inc. (dba SCS Global Services) independently spearheaded the development of the RF Protocol and made it available for public use to advance timely climate solutions. With the support of The International Centre for Integrated Mountain Development (ICIMOD), the RF Protocol was submitted to the Climate and Clean Air Coalition (CCAC) Scientific Advisory Panel (SAP). Members of the SAP conducted an independent review of the RF Protocol in 2023.

This published Version 2.0 incorporates subsequent technical updates to reflect the best available science as published in IPCC AR6 and subsequent publications.

Version 2.0 Updates

1.	SCS provided all technical updates for Version 2.0. The document reverted to an SCS Global Services document, available for general use without restriction.
2.	The Foreword has been updated.
3.	Minor editorial changes have been incorporated throughout text for clarity and explanation.
4.	Text sections, tables, and figures have been updated to incorporate new peer-reviewed research and data available at the time of publication of this version (January 2026).
5.	The brick kiln case study has been moved down from Section VI to the annexes.
6.	Radiative Efficiency values for CO_2 and the GHGs in Table A.2 have been updated to reflect values reported in IPCC AR6.
7.	The Bibliography was moved up from the bottom of the document. It now follows Section VI, preceding the Glossary of Key Terms and Abbreviations. The Bibliography has also been updated to follow APA style guidelines.

I. Goal

The RF Protocol is a practical application of IPCC-vetted climate science aimed at providing a comprehensive understanding of the climate benefits, co-benefits and trade-offs of various climate mitigation projects, as well as the timeframe of benefits realized by these projects.

Governmental pledges of climate action, including the updated 2025 Nationally Determined Contributions (NDCs) published before COP 30, have been widely recognized as important, but are still inadequate to meet the global temperature targets of the Paris Climate Agreement – namely, to hold “the increase in the global average temperature to well below 2°C above pre-industrial levels” and pursue efforts “to limit the temperature increase to 1.5°C above pre-industrial levels.”

Moreover, these pledges have been largely geared toward 2050 or beyond. However, given the Earth’s current energy imbalance, increased emphasis should also be placed on slowing near-term climate change, alongside longer-term goals. Without reducing radiative forcing levels by or before 2030 by at least 1.4 W/m^2 relative to projected business-as-usual values (based on AR5 RCP 8.5), longer term pledges, even if fully realized, will have a much-reduced probability of stabilizing the global temperature anomaly at or beneath 1.5°C above historical (pre-industrial) temperatures.[1]

The goal of the RF Protocol is to enable organizations to calculate the comprehensive radiative forcing impact of their activities (i.e., their RF footprint) and the extent to which their mitigation actions are reducing this footprint. This assessment tool covers emissions of well-mixed greenhouse gases, non-well mixed climate forcers, and non-emissions climate forcers such as changes in surface albedo. Through a better understanding of an organization’s climate impacts over all timeframes of interest (including both near-term and longer-term timeframes), the RF Protocol allows users to make better informed decisions on how best to align with the Paris Climate Agreement temperature goals.

[1] Future iterations of this document will explore updating the analysis to include IPCC AR6 Shared Socioeconomic Pathway (SSP) scenarios.

II. Background

Radiative forcing (RF) is the common, underlying metric by which all anthropogenic and biogenic factors influencing the climate system are evaluated. It is the basis upon which carbon dioxide equivalents (CO_2e) are calculated when determining the relative potency of greenhouse gases compared to carbon dioxide over various timeframes. The IPCC uses RF as the basis for modeling or presenting various climate scenarios.

The many drivers of increased RF include greenhouse gases (GHGs), aerosols and particulates, and changes in albedo. Over time, sustained increases in RF result in higher global surface temperatures (GST). Reducing RF is therefore essential to slowing the increase in the GST.

The RF Protocol will enable organizations to more effectively manage their contributions to climate change by identifying and implementing projects of sufficient scale and efficacy to reduce positive RF.

To date, GHG emissions have been the focus of GHG inventories and carbon footprints. The global warming potential (GWP) metric provides a means of comparing the relative climate potency of different greenhouse gases, typically over twenty years (GWP20) or one hundred years (GWP100), compared to carbon dioxide over an equal timeframe.

The RF Protocol allows organizations to consider all climate forcers over any timeframe, including well-mixed GHGs, non-well mixed GHGs and other short-lived climate pollutants, and surface albedo, to gain a broader understanding of their climate impact and consider the advantages and disadvantages of specific mitigation projects for the climate, the environment, and human health.

GWP calculations treat the radiative efficiency (RE) of CO_2 and other GHGs as a constant over a given timeframe. As a result, GWP calculations used in the marketplace today might be misleading by exaggerating the short-term effect of CO_2 reductions relative to reductions of short-lived climate forcers like methane, especially over longer time horizons such as the 100-year time horizon (GWP100). As discussed in *Climate Change 2021: The Physical Science Basis* (AR6), the RE of GHGs is reduced as atmospheric concentrations increase, because the infrared wavelength absorption for a given pollutant becomes increasingly saturated. To achieve the greatest accuracy, carbon footprints should have a means of incorporating these changes. The RF Protocol automatically adjusts RE values for a given point in time, consistent with the IPCC AR5's Representative Concentration Pathway (RCP) scenario modeling methods.

Beyond covering the emissions and non-emissions factors contributing to climate change, and staying abreast of changes in RE, there is a pressing need to address the temporal dimensions of climate change. IPCC reports of the past several years, including *AR6*, have called attention to the rapid and accelerating climate changes already underway. It has become clear that concerted actions are needed to reduce RF in the near-term (e.g., by 2030) to set the stage for longer-term strategies to be effective. The RF Protocol supports the calculation of RF inventories, RF footprints and RF reductions for organizations and projects in the near-term as well as over the longer term.

To ensure a full accounting, it is also vital – especially for projects – to keep track of the degree to which GHGs associated with a given mitigation project, or the project baseline against which it is compared, remain in the atmosphere for years after the initial emission. While these "legacy" GHGs – i.e., the fraction of past emissions of well-mixed GHGs that remain in the atmosphere and still contribute to current or projected forcing levels – are well understood, they are not typically integrated into carbon footprints. The RF Protocol makes it possible for RF inventories and RF footprints to include these legacy emissions, both now and over future time horizons.

All climate mitigation projects have potential co-benefits and trade-offs, but these advantages and disadvantages can be overlooked or not fully addressed. The RF Protocol includes co-benefit and trade-off analysis based on life-cycle assessment (LCA), specifically aimed at determining whether there are beneficial or adverse changes in air and water pollution, ecosystem disruption, rates of depletion of natural resources, and waste generation, with sufficient accuracy to determine the mitigation or offset value. Examples of co-benefits include improving regional air quality, reducing non-renewable energy or material resource use, and reducing toxic water emissions and waste. The LCA approach described in this document represents an important extension in scope for analyzing and justifying specific climate mitigation projects.

III. Scientific Basis

1. Consistency with IPCC Reports

The climate indicator algorithms and methods underlying the RF Protocol are derived directly from the methods used by the IPCC in its Fifth Assessment Report (AR5), *Climate Change 2013: The Physical Science Basis*, which made use of Representative Concentration Pathway (RCP) scenarios. AR5 modelled four Representative Concentration Pathway (RCP) scenarios projecting future trends in global emissions to find the resulting RF and temperatures, which included annual emissions, legacy emissions (i.e., GHGs accumulated in the atmosphere from the past that continue to contribute to climate change in the present), and projected increases in atmospheric concentrations of various climate pollutants.

The uncertainty in projected increases in total atmospheric concentrations was a principal justification for modelling the four scenarios. The worst-case projection, RCP8.5, assumed that industrial activity would proceed without significant reduction of the major contributors to rising RF, reaching an estimated 8.5 W/m^2 higher than pre-industrial levels by the end of the 21^{st} century, resulting in a modeled GST increase between 2.6°C and 4.8°C (IPCC, 2013), the hottest the planet has been in more than 5 million years (Scott and Lindsey, 2025). It is important to note that until now, despite all climate mitigation efforts to date, the increase in anthropogenic RF has continued to rise largely along the lines of the RCP 8.5 scenario.

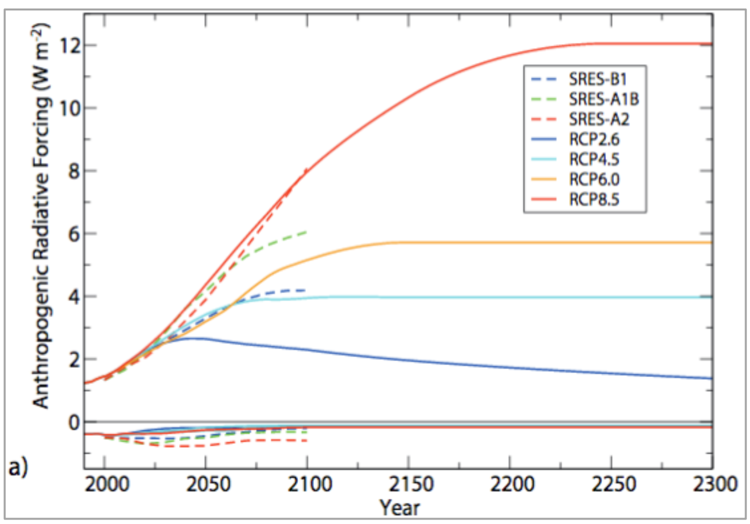

Figure 1. Representative Concentration Pathway Scenarios
(Source: IPCC AR5, Climate Change 2013: The Physical Science Basis, Figure 12.3)

The 2018 IPCC Special Report, *Global Warming of 1.5°*, used the RF-based RCP framework of AR5 to further examine mitigation scenarios for holding the GST anomaly below the +1.5°C or +2.0°C Paris thresholds, and to shed light on the differences in impacts at each of these levels. The report concluded that the global mean temperature would likely to cross +1.5°C as soon as 2040, or possibly even sooner, resulting in major environmental and human health consequences.[2] (At the time of publication of this document (2026), ample signals of such changes have been observed, such as storm intensification, wildfires, and coral reef degradation.)

Climate Change 2021: The Physical Science Basis, the first of the IPCC AR6 main assessment reports, extended this approach, using it to develop global temperature calculations for the Shared Socioeconomic Pathways (SSP), and to provide additional updates. This report, updated with more recent climate data and a re-assessment of the estimated climate response to radiative forcing, estimated that global warming of +1.5C° (evaluated over a 20-year average period) will likely occur in the early 2030s.[3] (In fact, World Meteorological Organization scientists concluded that 2024 was the hottest year on record, surpassing +1.5°C (WMO, 2025). Acceleration in the pace of warming can be attributed to three trends: the rise in emissions, the reduction of air pollutants that have had a negative radiative forcing influence, and natural climate cycles (Xu et al., 2018).

2. Key Features of the RF Protocol

The methods for calculating RF inventories and RF footprints are discussed in Section IV, with additional elaboration in Annexes A and B. Highlights of the calculation approach are summarized here:

- Consistent with the use of RF as the backbone of the IPCC RCP and SSP scenarios, RF calculations involve determining an emission inventory, by climate pollutant, for each year over a given time horizon. The radiative efficiency and atmospheric lifetime of each of these pollutants are then taken into consideration to assess the resulting RF, by pollutant, in each year of the time horizon. The RF contributions, by pollutant, across all years of emission, are added to determine the total. Finally, non-emissions-related RF is included.

- RF calculations cover the entire spectrum of climate forcers. These included well-mixed GHGs such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), hydrofluorocarbons and perfluorocarbons – as well as non-well mixed climate forcers (NWMCFs), including aerosols (sulphate, nitrate, ammonium, carbonaceous aerosols, mineral dust and sea spray) and chemically reactive gases. The RF is calculated by pollutant, based on its respective emission levels, radiative efficiency, and atmospheric lifetimes.

- RF calculations also include non-emissions-related RF. Generally, non-emissions RF includes four main components: changes in solar insolation, volcanic activity leading to the injection of sulfate aerosols into the upper atmosphere, waste heat, and changes in albedo. The RF Protocol can factor in all these changes, although in practical terms, changes in solar insolation and volcanic activity are unrelated to human activities and can be difficult to project into the future. This means that RF calculations in practical terms include non-emissions-related RF from albedo changes and waste heat (albedo changes being by far the dominant factor).

[2] According to IPCC SR 1.5, Summary for Policy Makers: "A.1 Human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels, with a likely range of 0.8°C to 1.2°C. Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate. (high confidence) (Figure SPM.1)." pg. 4 (IPCC, 2021).
[3] This assumes no major volcanic eruption, meteor impact, or other unanticipated natural phenomenon affecting the climate. From Section TS-9, pg. 42 of Arias, P.A., et al, 2021: Technical Summary. In Climate Change 2021: The Physical Science Basis. (IPCC, 2021)

- RF calculations include the time-varying radiative efficiency of trace GHGs. The GHGs each absorb infrared radiation in specific "absorption bands." These GHGs are translucent or opaque to radiation at these wavelengths. For example, CO_2 has two absorption bands around 3 µm and 4.5 µm. Radiation at this wavelength will be attenuated or blocked by CO_2 gas. As the concentration of these GHGs increases, more and more of the infrared radiation in these absorption bands is absorbed, eventually to the point where the absorption becomes "saturated" and no radiation can penetrate at all. After this point, adding more of the GHG will not cause any further absorption, because no more than 100% of all radiation at a given wavelength can be absorbed. This relationship between increasing GHG concentration and band saturation is precisely measured in laboratory settings. In short, for each incremental increase in the concentration of a GHG, its radiative efficiency will decrease. For example, the radiative efficiency of CO_2 decreases with increasing CO_2 ppm, as illustrated in Figure 2 below. In 100 years, if CO_2 concentrations increase as estimated in the RCP 8.5 Scenario, the radiative efficiency of CO_2 will be roughly 64% less than it is today, meaning each incremental ton of CO_2 emitted will have 64% less radiative impact at that time.

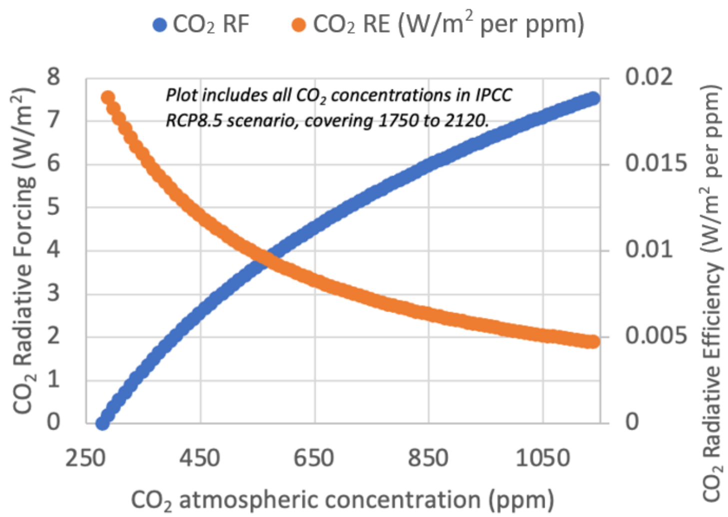

Figure 2. The relationship between increasing CO_2 concentration in the atmosphere (ppm), Radiative Forcing, and Radiative Efficiency. The Radiative Efficiency of CO_2 decreases with increasing CO_2 concentration. This chart shows the CO_2 ppm from 1750 (278 ppm) projected to 2120 in the RCP8.5 Scenario. From Expressions for Calculation Radiative Forcing, available on NOAA website, although itself was derived from the IPCC 2001 Second Assessment Report.

- For NWMCFs, RF calculations include variations in RF per unit based on the location, time, and source of emission. NWMCFs, depending on where and when they are present in the atmosphere, as well as other physical characteristics unique to different emissions sources, can have greatly varying radiative effects. For example, black carbon emissions from biomass burning (e.g., burning of agricultural residues) tend to be emitted during summertime and fall, when the sun is in the sky for the longest. This means that black carbon emissions from biomass generally have relatively elevated RF effects, since it is emitted precisely when its effects (absorption of sunlight) are strongest. If black carbon particulate matter deposits on snow and ice, it can darken high albedo surfaces, hastening their melting. The snow or ice may melt to reveal lower albedo ground or water surface, further increasing radiative forcing impacts. Therefore, black carbon emitted near snow or ice will have a relatively higher radiative efficiency.

- RF calculations can be applied to any time horizon – past, present, or future – over any length of time. RF calculations include the assessment of legacy emissions – the fraction of past emissions remaining in the atmosphere which continue to contribute to RF at a given point in time.

3. Complement to GWP-Based Accounting

The RF Protocol is a crucial complement to GWP-100 based accounting, which underlies most climate policies administered by governments and privately operated organizations. The major similarities are:

- The two accounting protocols both rely on the same methods and data – radiative efficiency, atmospheric lifetime, and inventory data – to derive CO_2 equivalencies.
- GWP-100 and RF-based accounting protocols both provide coverage of the entire range of GHGs – carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), hydrofluorocarbons and perfluorocarbons.

The primary dissimilarities center around the facts that:

- In addition to annual GHG emissions, the RF Protocol has the capacity to include non-well mixed climate forcers, non-emissions forcers, and both positive and negative forcers;
- The RF Protocol takes into account the environmental variables relevant to short-lived climate forcers, including regional variability, precursor emissions, ground deposition, feedback loops, and steady-state atmospheric concentrations;
- RF inventories and RF footprints can be integrated over any timeframe, factoring in the time-varying reduction in GHG radiative efficiency, with the capacity to examine the near-term (any time period from 1 year up to 20 years), mid-term (21-50 years), and longer-term (51 years and longer) effects of mitigation projects and initiatives; and
- The RF Protocol includes a specific, life-cycle assessment-based approach to support co-benefit and trade-off analysis (SCS, 2023).

4. Comparison to GTP

The global temperature change potential (GTP) is another RF-based metric that has been discussed. GTP compares the absolute change in global surface temperature at a chosen point in time in response to an emission pulse relative to the temperature change that would be caused by the emission of an equal amount of CO_2. While GTP expresses results in terms of temperatures, GTP is also based upon quantifications of RF, since RF leads to temperature changes.

The GTP metric is similar to RF in that it is tied to a specific target year in the future against which to measure effect. However, GTP is dissimilar to RF in that it is focused on temperature, a later node in the stressor-effect network that links climate forcers to climate change effects (Annex C). This difference introduces significant additional uncertainty into GTP quantifications because the uncertainty of the climate response in terms of temperature is very high. (IPCC AR5 notes that there is a 3-fold uncertainty in the "climate sensitivity" parameter linking RF to temperature changes.) The RF metric, by contrast, avoids this uncertainty by focusing strictly on the change in radiative forcing at specific points in time.

Additionally, GTP does not capture the full range of non-gaseous NWMCFs, and it does not include the effects of non-emissions climate forcers, negative climate forcers, or legacy GHGs.

IV. Scope

This document describes the steps involved in establishing an RF inventory and RF footprint, assessing an RF reduction, and conducting co-benefits and trade-off analysis. These steps will enable organizations to assess their contribution to RF and will incentivize organizations to consider a broad range of projects aimed at mitigating both emissions and non-emission sources of RF to achieve timely results. The RF Protocol includes a screening framework for determining the suitability of any given RF reduction project, taking into consideration climate benefit (i.e., amount and timing of RF reduction), technological feasibility, scalability, and environmental and human health co-benefits and trade-offs.

In addition, this document briefly discusses the global RF reduction needed by 2030, and the part that various RF mitigation approaches focused on short-lived climate forcers might play in this reduction. It also provides a theoretical case example – a scalable project aimed at significantly reducing carbon dioxide, black carbon and particulate emissions, along with associated RF and air pollution impacts, from brick kilns operating in the Hindu Kush Himalaya region (Annex F).

V. RF Calculations

1. Principles

The following principles should be applied when conducting RF calculations:

- *Relevance:* RF-related information, data and methodologies are applicable to the intended user and the scope of assessment.
- *Completeness:* Known information and data pertaining to RF assessment are included in analyses, as well as known relevant information to support criteria and procedures.
- *Consistency:* Information produced by analyses supports meaningful comparisons.
- *Accuracy:* Bias and uncertainties are considered and minimized to the degree practical.
- *Transparency:* Sufficient information is disclosed to support decisions by intended users with reasonable confidence.
- *Conservativeness:* Conservative assumptions, values and procedures are applied.
- *Scale:* RF reduction levels are considered in the context of the amount of global RF reduction needed to meet RF stabilization targets (Annex B) over various time horizons.

2. Scope of Climate Forcers Included

RF calculations for organizations and projects should address all relevant climate forcers (Table 1), following transparent, documented procedures. This includes:

- annual and accumulated RF from well-mixed GHGs (WMGHGs);
- annual RF from non-well-mixed climate forcers (NWMCFs); and
- non-emissions RF-related changes in albedo.

Climate forcers are considered relevant if they are associated with an organization's or project's activities. (If it is not feasible to assess a given climate forcer, due to data availability or other restrictions, then this should be stated in conjunction with the RF inventory.)

RF calculations should include emissions and radiative effects that are increased or decreased by the organization, or as a result of the project, and should consider uncertainties in emissions and radiative effects (Annex A).

Table 1. Key Climate Forcers

Climate Forcers Contributing to Net Positive RF	*Climate Forcers Contributing to Net Negative RF*
Well-mixed greenhouse gases	**Well-mixed greenhouse gases**
Carbon dioxide (CO_2)	None
Methane (CH_4)	
Nitrous oxide (N_2O)	
Greenhouse gas categories that include both well-mixed and non-well-mixed climate forcer species 1)	**Greenhouse gas categories that include both well-mixed and non-well-mixed climate forcer species**
Chlorofluorocarbons (CFCs)	None
Hydrochlorofluorocarbons (HCFCs)	
Hydrofluorocarbons (HFCs)	
Chlorocarbons and Hydrochlorocarbons	
Bromocarbons, Hydrobromocarbons and Halons	
Fully Fluorinated Species	
Halogenated Alcohols, Ethers, Furans, Aldehydes and Ketones	
Non-well-mixed climate forcers 2)	**Non-well-mixed climate forcers**
Black carbon	Nitrate aerosols
Brown carbon	Organic carbon
Tropospheric ozone from non-methane precursors, including NOx 3), CO, and VOCs	Sulfate aerosols
Miscellaneous Compounds 4)	
Non-emission climate forcer	**Non-emission climate forcer**
Decrease in Albedo	Increase in Albedo
Waste Heat	

1) This grouping covers GHG categories that include both well-mixed and non-well-mixed species. A comprehensive list of GHGs and their atmospheric lifetimes can be found in IPCC (2021) AR6 WG1 "7.SM Chapter 7: The Earth's energy budget, climate feedbacks, and climate sensitivity - Supplementary Material, Table 7.SM.7. *https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_FGD_Chapter07_SM.pdf*

2) Neither mineral dust nor water vapor are currently included in the corporate analysis. Mineral dust is primarily a negative climate forcer, but can also cause warming, depending on the iron and aluminum content and the particle size (Jacobson, 2001). Water vapor is a positive climate forcer, but is primarily associated with natural processes rather than anthropogenic sources.

3) Tropospheric ozone is a potent climate forcer, but the chemical pathway for its formation is complex. Some portion of ozone formation can be attributed to methane as a precursor, and is therefore included in methane accounting. The remaining anthropogenic ozone is formed by other precursors, and is referenced here. The RF attributable to an emission of NOx is highly variable depending upon region of emission and season of emission, and may also vary greatly year-to-year. Site-specific atmospheric modeling is required for accuracy, but is also generally impractical. Therefore, the accounting of the RF effects from tropospheric ozone precursors including NOx, while desirable, remains aspirational at this time.

4) A comprehensive list of miscellaneous compounds can be found in IPCC (2021) AR6 WG1 7.SM Chapter 7: Table 7.SM.7

3. Timeframe of Analysis

The analysis timeframe for RF calculations should be a defined "period of interest" to the organization, which can include past, present and future years, or in the case of a project, a period of interest to the project, from onset to future years. The period of interest includes the set end date(s) relevant to organizational or project goal(s).

In addition, the analysis should include the subsequent period of projected persistent WMGHG-related RF changes that will occur beyond the defined period of interest, including the short term (e.g., 10-20 years), medium term (e.g., 20-50 years), and long term (e.g., 50 years, 100 years). Assumptions, limitations and reasoning for choosing a given timeframe should be provided.

4. Calculating the RF Inventory and RF Footprint

RF inventories and RF footprints should be calculated for individual years over the timeframe of analysis. The annual RF inventory and RF footprint are based on the effective RF at the end of each specified year.

4.1 RF inventory

RF inventories include all positive and negative climate forcers:

- WMGHGs (e.g., CO_2, CH_4, N_2O, SF_6, HFCs, PFCs)
- Non-well-mixed climate forcers (NWMCFs), including particulate matter (e.g., black carbon) and short-lived gases (i.e., separately reporting tropospheric ozone, CO, organic carbon)
- Non-emissions climate forcers (e.g., changes that increase or decrease albedo)

4.2 Radiative Forcing (RF) footprint

An aggregated RF footprint should be calculated as shown in Equation 1, which includes:

- all positive climate forcers from emissions, as well as removals of positive climate forcers;
- additional positive radiative forcing resulting from a decrease in magnitude of negative climate forcers over the timeframe of analysis; and
- net positive radiative forcing resulting from changes in surface and non-emissions-related albedo.

Unlike RF inventories, RF footprints generally leave negative forcers out of the aggregation to avoid "giving credit" for adding cooling aerosols which are also harmful to human health and the environment. These aerosols are included only when they are reduced, to account for the extra warming effect such a reduction would cause.

Equation 1. Quantifying the aggregated positive RF (i.e., RF Footprint).

$$\text{Aggregated positive RF} = \left(RF_i + RF_j + RF_k + RF_l + RF_m\right)_{tF}$$

Where:

- *tF* represents the timeframe of analysis for the annual RF footprint or integrated RF footprint
- RF_i represents positive RF from WMGHG emissions (annual and legacy emissions)
- RF_j represents positive RF from NWMCF emissions
- RF_k represents positive RF from secondary climate forcers formed from precursor emissions (e.g., tropospheric ozone)
- RF_l represents positive RF from changes in non-emissions climate forcers (e.g., albedo)

- RF_m represents the positive RF due to the reduction in magnitude of negative climate forcers

NOTE 1: Reductions in positive RF resulting from climate forcer removal are captured in i, and j but should also be reported separately for transparency

NOTE 2: Additional equations used to quantify specific RF inventory values are provided in Annex A.

4.3 Calculation metrics

The annual RF inventory and RF footprint calculated for an organization or project should be quantified as the calculated global mean watts per square meter (W/m^2), consistent with standard reporting of RF values. These may be converted into standard energy units such as joules.

In addition, to facilitate layperson, policymaker and other decision-maker understanding and comparisons, such results may also be normalized to carbon dioxide, as forcing equivalents, CO_2fe (Equation 2, Annex D). These RF values should be calculated at multiple points in time, in the near term, medium term, and long term.

Equation 2. Determining CO_2fe

$$RF[tCO_2fe] = \frac{RF\left[\frac{W}{m^2}\right]}{RE_{CO_2}\left[\frac{W}{m^2 \cdot t}\right]}$$

Where:

- *RF* is Radiative forcing
- *RE* is Radiative efficiency
- *t* is tonnes

The radiative efficiency (RE_{CO2}) value of 1.7008×10^{-12} $W/(m^2$ tonnes) derived from IPCC AR6, Table 7.SM.7 is currently used, but should be updated over time as the CO_2 concentration and RE values change. The integrated RF inventory and RF footprint should be quantified in watt-years per square meter ($W \cdot yrs/m^2$).

5. Data Collection

5.1 Types of data

Organizations, project developers, and project implementers should collect site-specific data for activities under the financial or operational control of the organization undertaking the RF assessment, as well as for activities beyond direct financial or operational control that contribute a significant percentage to the RF inventory or footprint (Scopes 1, 2 and 3) data.

NOTE: Site-specific data refer to either direct climate forcer emissions (determined through direct monitoring, stoichiometry, mass balance, or similar methods), activity data (inputs and outputs of processes that result in climate forcer emissions or removals) or emission factors. Site-specific data can be collected from a specific site or can be averaged across all sites that contain the activities under study. They can be measured or modelled, as long as the result is specific to the process in the product's life cycle.

- Data should be representative of the processes for which they are collected.
- Primary data that are not site-specific should be used when the collection of site-specific data is not practicable.

- Secondary data should only be used for inputs and outputs when the collection of primary data is not practicable, or for processes of minor importance. Secondary data should be justified and documented.
- The best quality data should be sought to reduce bias and uncertainty. Data quality should be characterized by both quantitative and qualitative aspects.
- Organizational data collection should include all relevant annual climate forcers.

While WMGHG emissions have well-characterized RF levels, the RF levels of non-well-mixed climate forcers (NWMCFs) can be highly variable on a regional and global level, as well as in time. For each NWMCF, spatial and temporal characterizations (which can include underlying surface albedo, cloud cover, dispersion, and atmospheric lifetime data) should be considered in the data quality analyses.

NOTE: National and provincial or state governments could additionally use this approach to account for climate forcer emissions from wildfires within their jurisdictional borders.

5.2 Specific Data Collection Guidance for Selected Climate Forcers

Guidance for data collection for selected climate forcers is provided. Data collection for GHGs and other climate forcers follow widely established procedures.

- **Black carbon and other carbonaceous aerosol emissions**
  For black carbon and other carbonaceous aerosols, the radiative efficiency and atmospheric lifetime used to quantify RF from these emissions is specific to the region of the emission. The source types, seasonality, and number of emission sources vary dramatically region-to-region for black carbon emissions. As a result, black carbon radiative efficiency values and atmospheric lifetimes used to quantify RF differ between regions. Sectors within each region will have different data collection and quantification needs.

- **Radiative forcing from albedo change**
  Radiative forcing from albedo change is quantified by considering the intensity of incoming radiation, atmospheric transmittance and the change in albedo. The intensity of incoming radiation can be retrieved from various atmospheric databases (e.g., NASA) or numerical simulation models such as weather and forecasting models. The annual global mean value of atmospheric transmittance, which is 0.730, can be considered for the calculation of surface albedo-induced RF. This transmittance should be adjusted to account for the cloudiness of different areas (surface albedo changes having a lesser effect in regions with relatively more clouds).

5.3 Specific Data Collection Guidance for Large Geographic Regions

- **CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, NF_3, SF_5CF_3, halogenated ethers, other halocarbons reported under UNFCCC**
  Data collection and reporting for national organizations is consistent with the UNFCCC reporting requirements for national GHG inventories.[4]

[4] For example, https://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf

- **Black carbon**
  The RF resulting from black carbon is first evaluated with modeled emissions inventories calculated by multiplying measures of activity (e.g., liters of diesel fuel consumed) with emissions factors (e.g., grams black carbon per liter diesel fuel combusted). These modeled emissions inventories are based upon well-documented activity levels and publicly reported emissions factors that account for local conditions, including combustion type, seasonality and other considerations affecting the amount of black carbon emitted. However, because modeled emissions inventories for black carbon usually significantly understate emissions, the modeled emissions data should be adjusted to be consistent with satellite-based emissions assessments, if available, which are often more accurate and more complete. The method used in Bond et al. (2013) should be the basis of this adjustment, whereby adjustment factors are used to scale the black carbon emissions to their appropriate level. To the extent possible, black carbon emission estimates are generated using multiple methods and data sources, then compared in a sensitivity analysis to help assure robustness. The approach for quantifying black carbon emissions used in the RF inventory and RF footprint should be described.

- **Tropospheric ozone**
  Emissions inventories for NOx (a tropospheric ozone precursor) are quantified using methods that are consistent with country criteria air pollutant programs (e.g., in the U.S., the Environmental Protection Agency has historically tracked NOx emissions in the National Emissions Inventory). To the extent possible, emissions inventories for NOx emissions are also calculated using empirical satellite measurements of column concentrations of NO_2, O_3, HNO_3, and CO (e.g. Miyazaki et al. (2016)). Satellite-based emissions estimates are compared with existing emissions inventories. The approach for quantifying NOx emissions used in the RF inventory and RF footprint should be described if NOx RF is included.

- **SO_2 emissions**
  SO_2 emissions are tracked in the key sectors of coal-fired power generation, fuel combustion used to operate vehicles and equipment (especially diesel vehicles), refineries, and metallurgical facilities using coking coal. SO_2 emissions in these sectors are quantified based on emissions inventories. The total national emissions are compared to satellite data regarding SO_2 concentrations over the country. Adjustments to the emission inventory for SO_2 should be made if a major discrepancy between the satellite data and emissions inventory exists. Adjustments could take the form of multiplying the SO_2 emissions inventory by a factor which represents the ratio of regional SO_2 emissions derived from satellite-based data to emissions inventory-based data, or other approaches.

- **CO and VOCs**
  For carbon monoxide (CO) and volatile organic carbons (VOCs), emissions are first evaluated with modeled emissions inventories calculated by multiplying measures of activity with emissions factors. These are then compared with and adjusted as needed to existing country-level inventories. Historical emissions may be tracked to the extent that the radiative influence has a measurable effect on the RF inventory and RF footprint.

5.4 Emissions data collection time period

Annual emissions data for organizations should be collected for at least the most recent 12-month period for which data are available.

For organizations choosing to establish their historic footprint as the basis for comparison, data should also be collected for as long a historical period as is sufficient to capture at least 95% of the organization's total current forcing levels, including its legacy GHGs. If this level of completeness is not attainable, then the organization should report the available data used for the analysis and state the limitations in completeness.

The source of inventory data (e.g., activity-based versus satellite-based emissions data) can potentially have a large impact on results. As such, data sources should be selected that are comparable over the analysis timeframe so that changes in emissions reflect changes in the system under study rather than differences in data sourcing methods or modelling parameters. The sources of inventory data should be documented.

VI. Establishing a 2030 RF Reduction Roadmap

1. Global RF Reduction Needed Now

The first step in establishing a global RF reduction roadmap is to identify the global surface temperature (GST) target, then identify the corresponding RF anomaly threshold. This process, which can be applied to any time horizon, is described in Annex B. Given the goal of maintaining GST at or below +1.5°C, then the RF anomaly should be stabilized at or below +1.9 W/m^2.

AR6 reported that the world has already exceeded this level, reaching an RF anomaly of +2.72 W/m^2 in 2019 (IPCC, 2021) from pre-industrial levels. As of 2024, this value is estimated to have risen to more than +2.97 W/m^2 relative to 1750 (Forster et al., 2025). Given the projected rate of continued increase in global RF, it has been calculated that at least 1.4 W/m^2 should be removed from the atmosphere by 2030. Additional efforts to reduce global RF will be required in subsequent decades (see Figure B.1 in Annex B). Failure to reduce RF will lead to increased sustained RF levels and ultimately to temperature "overshoots" above +1.5°C that will introduce increasing uncertainty and significantly compromise the ability to stabilize climate below 1.5°C over time.

2. The Importance of CO_2 Reduction

Currently, it takes the reduction of approximately 57 billion metric tons of atmospheric CO_2 to prevent an additional 0.1 W/m^2 in total RF over one year, since the inherent CO_2 radiative efficiency is extremely low. Given that annual emissions of CO_2 are also in the tens of billions of metric tons, the RF reduction benefits of CO_2 reductions achieved between now and 2030 will not be realized until future decades, even with the advances in carbon dioxide removal technologies. To achieve the RF reduction required in the near-term, it will be necessary to employ additional strategies, while simultaneously recognizing that CO_2 reduction projects and projects targeting other long-lived GHGs remain essential to reduce ongoing emission streams, to reduce future legacy emissions, and to reduce ocean acidification.

3. Aligning RF Reduction Goals with Temperature Targets

The RF Protocol provides a basis for aligning the RF reduction goals of projects with temperature targets by estimating the RF reduction potential (RFRP) of such projects. This ability supports organizations' efforts to prioritize projects in terms of their relative efficacy, potential trade-offs, timing of RF reductions (near-term, mid-term or long-term) and costs.

4. Reduction of Short-Lived Climate Forcers and Steps to Restore Albedo are Vital

Some projects, such as those which mitigate short-lived climate forcers, have been recognized for their ability to reduce RF in the short term. The Climate and Clean Air Coalition, for instance, is a leader in promoting projects focused on mitigation of SLCFs. Projects focusing on the reduction of SLCFs are a key part of any 2030 RF Reduction Roadmap, and can be quite effective in reducing net RF. That said, these projects alone are not sufficient to achieve the goal of net reduction of 1.4 W/m^2 by 2030 required for stabilization of GMT anomaly at or below +1.5°C.

Table 2 shows preliminary estimates for some possible approaches for near-term RF reduction before 2030, and over longer time horizons, based on the reduction of SLCFs.

Table 2. Estimated RF reduction potential (RFRP) of SLCFs based on project categories **in various industry sectors, calculated for 2030 and 2050.**

Mitigation Pathways	*Project Industry Sectors*	*RFRP 2030*	*RFRP 2050*
Methane	Various projects – e.g., natural gas, agriculture, waste management sectors ***Assumes 40% decrease in emissions over next 5 years***	0.2 W/m^2	0.4 W/m^2
Black carbon	Various projects – e.g., Brick Kiln project, transportation, agriculture, industrial sectors ***Assumes 30% reduction in emissions over the next decade***	~0.1 W/m^2 (globally) (2-3 W/m^2 regionally)	~0.1 W/m^2 (globally) (2-3 W/m^2 regionally)
Tropospheric ozone	Various – e.g., industrial, transportation sectors, atmospheric abatement. ***Assumes urban smog reduced by at least 50%***	0.2 W/m^2	0.2 W/m^2

Likewise, projects aimed at increasing surface albedo are a vital part of the mix of strategies to be implemented in the near-term. Projects aimed at increasing the albedo of infrastructure and buildings, such as “cool roofs” and “cool streets,” can provide immediate RF reduction benefits and help slow the urban heat island effect, with all of its attendant health impacts, that is challenging many cities.

In the near-term, these SLCF are up to thousands of times stronger than CO_2. While the warming effect of CO_2 builds slowly, these pollutants act fast, trapping large amounts of excess atmospheric heat as soon as they are emitted. In addition, man-made alterations of the earth’s surface and feedback loops have led to serious reductions in the Earth’s albedo, impacting its RF effects. If we can curb these SLCPs and protect and restore the earth’s albedo at scale, we can begin to slow down the rise in excess heat trapped in atmosphere in the crucial next ten years, build a bridge to net zero by 2050, and move more rapidly toward a sustainable climate. This requires accurate accounting of all heat drivers across all time scales.

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Glossary of Key Terms and Abbreviations

albedo
proportion of sunlight (solar radiation) reflected by a surface or object, often expressed as a percentage

NOTE: Clouds, snow and ice usually have high albedo; soil surfaces cover the albedo range from high to low; vegetation in the dry season and/or in arid zones can have high albedo, whereas photosynthetically active vegetation and the ocean have low albedo.

albedo restoration
returning the current reduced albedo intensity back to its historic baseline conditions

baseline scenario
documented reference case that best represents the current or original conditions that exist in the absence of a RF reduction project

carbon dioxide equivalent (CO_2e)
unit for comparing the integrated RF due to a pulse emission of a given RF component, relative to the integrated pulse emission of an equal mass of CO_2 over an equal period of time

carbon dioxide forcing equivalent (CO_2fe)
unit for comparing the instantaneous RF caused by a climate forcer to the RF caused by one kilogram of carbon dioxide in the atmosphere at a selected point in time

NOTE: The unit for an atmospheric substance is one kilogram. The unit for albedo change is the total change in net albedo over a specified surface area and resulting radiative forcing change.

climate
statistical description of weather in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years

climate forcer
any external driver of climate change that causes a positive or negative change in RF (e.g., an emission, substance, process, activity or change in state)

climate forcer removal
extraction, sequestration, destruction or conversion to lower potency of a climate forcer

NOTE: Examples include carbon dioxide removal through the process of photosynthesis or facilitated through direct air capture or bioenergy with carbon capture and storage. In the case of tropospheric ozone, ozone destruction can take place naturally through the formation of hydroxyl radicals, through a catalytic process of bromine oxide converting ozone into oxygen, or through other mechanisms.

Earth energy imbalance (EEI)
A difference between incoming radiative energy from the Sun and outgoing radiative energy from the Earth measured over a period of time

NOTE. A positive imbalance means the Earth system is gaining net heat energy.

environmental mechanism

the physical, chemical and biological processes for a given impact category that link life cycle inventory analysis results to category indicators and endpoints

global mean surface temperature (also referred to as "global surface temperature")
estimated global average of near-surface air temperatures over land and sea ice, and sea surface temperature (SST) over ice-free ocean regions, with changes normally expressed as departures from a value over a specified reference period

NOTE: The reference period 1850–1900 is used to approximate pre-industrial global mean surface temperature (GMST). When estimating changes in GMST, near-surface air temperatures over both land and oceans are used.

global warming potential (GWP)
time-integrated radiative forcing due to a pulse emission of a given component, relative to a pulse emission of an equal mass of CO_2

greenhouse gas (GHG)
gaseous constituent of the atmosphere, either natural or anthropogenic, that absorbs and emits radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere, and clouds

NOTE: GHGs include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6). Other examples of GHGs are provided in IPCC Assessment Reports. Water vapor, which is an anthropogenic as well as natural GHG, is not included in the calculation of the RF inventory or RF footprint because the total amount in the atmosphere is controlled by the temperature and atmospheric circulation rather than emissions of water vapor.

impact
change, adverse or beneficial, caused by the process being assessed

impact category
class representing environmental issues of concern to which life cycle inventory analysis results may be assigned

NOTE: "Environmental issues of concern" include impacts to human health, such as from air pollutants.

life cycle assessment (LCA)
quantitative, cradle-to-grave assessment of the biophysical impacts of an RF project on the environment and human health from extraction of resources, distribution, use and disposal

NOTE: LCA is an internationally recognized assessment methodology. This definition is scoped specifically to the purposes of this document.

legacy GHGs (also called accumulated GHGs)
the fraction of residual well-mixed greenhouse gas emissions that remain in the atmosphere at a specified point in time

non-emission climate forcer
a process or activity other than an emission source that leads to a change in RF.

NOTE: A change in surface albedo and waste heat are examples of non-emissions climate forcers.

non-well-mixed climate forcer (NWMCF)
climate forcer with atmospheric concentration that is strongly heterogeneous throughout the Earth's troposphere

NOTE: NWMCFs typically have an average atmospheric lifetime much less than the mixing time of the Earth's atmosphere, remaining in the troposphere for days to weeks (e.g., sulphates, carbonaceous aerosols, water vapor emitted due to human activities), weeks to months (e.g., tropospheric ozone that results from other chemical precursors), or seasons in a year. Mixing over the globe typically, if at all, takes a year or two. Thus, NWMCFs are considered short-lived climate forcers (also called short-lived climate pollutants). Typically, the atmospheric concentrations are significantly higher near large, continuous emission sources than in other regions.

organization
government, corporation, firm, enterprise, authority, partnership, charity, institution or other entity that has its own functions with responsibilities, authorities, and relationships to achieve its objectives

pre-industrial period
multi-century period prior to the onset of large-scale industrial activity around 1750

NOTE: Pre-industrial period conditions are used by the IPCC as a reference for the RF and GST anomalies, but the term is not included here to serve as a project baseline, nor is it included to suggest that the climate system can be returned to this status.

project
a planned activity or process that has the ability to reduce RF

project category
a class of projects having shared characteristics that have the ability to reduce RF

project scenario
hypothetical case that best represents the conditions most likely to occur due to implementation of a proposed RF reduction

project developer
individual or organization that has overall control and responsibility for an RF reduction project

projected persistent WMGHG
retained atmospheric fraction of current or legacy well-mixed greenhouse gas emissions over specified future time periods

radiative efficiency (RE)
net change in RF per unit increase in climate forcer atmospheric concentration

radiative forcing (RF)
change in the net, downward minus upward, radiative flux, expressed in Watts per meter squared (W/m^2) at the top of the atmosphere due to an external driver not associated with climatic feedback loops

NOTE: RF can be measured globally or regionally. RF results from a change in an external driver of climate change, such as a change in the concentration of carbon dioxide or the output of the sun. Consistent with IPCC documents, RF refers to a change relative to the year 1750 unless otherwise noted. RF calculated in accordance with this protocol is consistent with Effective Radiative Forcing defined by IPCC, and includes rapid adjustments on clouds including indirect and semi-direct forcing cloud effects resulting from aerosols.

radiative forcing reduction
quantified decrease in RF between a baseline scenario and a project scenario

radiative forcing reduction potential
amount of RF reduction determined to be achievable by a project or project category

radiative forcing project
planned activity (or activities) that reduces RF

radiative forcing footprint
sum of the RF associated with the relevant climate forcer emissions, legacy GHGs, non-emission climate forcers, and climate forcer removals, both direct and indirect RF values for all relevant positive and negative climate forcers, quantified and expressed in a disaggregated manner

NOTE: A negative climate forcer may only be included in the aggregation if it is decreasing in magnitude, thus resulting in a positive radiative forcing effect.

radiative forcing inventory
RF values for all relevant positive and negative climate forcers, quantified and expressed in a disaggregated manner

representative concentration pathway (RCP)
modeled scenario from IPCC AR5 that includes time series of emissions and concentrations of the full suite of greenhouse gases and aerosols and chemically active gases, as well as land use/land cover

stressor-effects network
the modeled cause-effect biophysical pathway from stressor to midpoint(s) and final endpoint(s) for a specific impact category

trade-off
adverse environmental or human health consequences that could occur as the result of an operational change or RF reduction

well-mixed greenhouse gas (WMGHG)
GHG with a lifetime sufficient for it to potentially disperse throughout the Earth's troposphere

NOTE: These gases have an average atmospheric lifetime longer than the mixing time of the Earth's atmosphere. There is some spatial heterogeneity for their concentrations, but it is relatively small. For example, the CO_2 concentration varies across the atmosphere at any time by ±1-2%. Methane has a much shorter atmospheric lifetime than other well-mixed greenhouse gases, and is therefore often referred to as a short-lived climate pollutant.

Abbreviations and Acronyms

AR5	IPCC Fifth Assessment Report
AR6	IPCC Sixth Assessment Report
CCAC	Climate and Clean Air Coalition
CFC	chlorofluorocarbon
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalents
CO_2fe	carbon dioxide forcing equivalents
EEI	Earth energy imbalance
g	gram
GHG	greenhouse gas
GST	global surface temperature
GTP	global temperature change potential
GWP	global warming potential
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
ICIMOD	International Centre for Integrated Mountain Development
IPCC	Intergovernmental Panel on Climate Change
J	joules
kg	kilogram
km	kilometer
LCA	life-cycle assessment
m	meter
NWMCF	non-well mixed climate forcer
ppm	parts per million
ppb	parts per billion
RCP	representative concentration pathway
RE	radiative efficiency
RF	radiative forcing
RFRP	radiative forcing reduction potential
SR1.5	IPCC Special Report: Global Warming of 1.5°C
t	metric tonne (1,000 kg)
TJ	terajoules
TO	tropospheric ozone
VOC	volatile organic compound
W/m^2	watts per meter squared
WMO	World Meteorological Organization
UNFCCC	United Nations Framework Convention on Climate Change

RADIATIVE FORCING PROTOCOL
METHODS AND APPLICATIONS

ANNEXES

Annex A

Quantification of Radiative Forcing

This Annex expands on the concepts referenced in the document, describing methods and equations used to quantify global RF attributable to project categories, projects, and organizations. Throughout this Annex, default factors are presented for use in equations. These default factors are based on conservative assumptions that will result in upper-bound estimates in quantified results, which are improved by performing site-specific modelling with higher temporal and geographical representativeness. Specific data, rather than default data, are used to assess results for better temporal and geographical representativeness.

A.1 Equation for Quantifying RF

RF is quantified in each year using RF Protocol Equation 1.

Equation A. 1 General equation for quantifying RF for a given year (t_F) considering all climate forcer effects occurring between t_0 and a later time t_F, expressed in W/m² or CO_2fe

$$RF(t_F) = RF_{WMGHG}(t_F, t_0) + RF_{TOPr}(t_F, t_0) + RF_{NWMCF}(t_F, t_0) + RF_{non-emission\ CFs}(t_F)$$

Where:

- t_F is the year in which the radiative forcing value is calculated (i.e., the most recent 12-month period for which data are available)
- t_0 is the first year in the analysis timeframe
- RF_{WMGHG} is the radiative forcing from emissions of well-mixed greenhouse gases, including the influence of legacy emissions on current RF
- RF_{TOPr} is the positive radiative forcing from secondary climate forcers formed from tropospheric ozone precursors
- RF_{NWMCF} is the radiative forcing from non-well-mixed climate forcers
- $RF_{non-emission\ CFs}(t_F)$ is the radiative forcing in year t_F from activities that are not associated directly with emissions

NOTE: Negative RF is not included in an aggregation used for calculating RF footprints, except for negative forcers of decreasing magnitude.

A.2 Climate Forcers Included in RF Reduction Potential Analysis

All emissions and activities that can be linked to positive and negative RF are included across the entire analysis timeframe. This includes all known emissions that cause direct RF, as well as those that lead to radiative forcing indirectly, through effects such as chemical reactions in the atmosphere and effects on cloud cover (see Table 1 in the RF Protocol).

There might be activities affecting global or regional RF that are not associated directly with emissions. The following activities are known to induce RF changes ($RF_{non-emission\ CFs}$), and are included, provided that the scale of the RF change related to the considered activity is significant:

- Deposition of black carbon and other darkening materials on ice surfaces (which are accounted for when quantifying the RF related to black carbon emissions);
- Infrastructure-related land use changes that lead to a change of surface reflectivity;
- Albedo restoration (i.e., returning albedo to its pre-industrial period conditions, such as through eliminating destruction of Arctic sea ice due to ship ice breaking, especially in spring and summer months, which removes high-albedo ice and replaces it with low-albedo seawater);
- Brightening (i.e., “cool roofs” or “cool roads”) or darkening (i.e., from infrastructure construction) of urban areas, which can cause changes;
- Other land use changes, leading to either positive or negative RF changes (depending on the albedo modification); and
- Destruction of stratospheric ozone by Ozone Depleting Substances, especially by CFCs (which are accounted for when quantifying the RF related to CFC emissions).

If the effect on RF is material given the analysis scope, such activities are included, and a trade-off analysis is also included to determine any negative consequences.

A.3 Quantifying RF from Emissions

The RF related to emissions is quantified using Equation A.2.

Equation A. 2 Calculating the RF of a specific species of climate forcer over a defined analysis timeframe (t_F) from all sources

$$RF_{climate\ forcer}(t_F) =$$

a. For WMGHGs:

$$\sum_{i=WMGHG\ source} \int_{t_0}^{t_F} E_i(t_o) \times \mu RF(t)\, dt$$

b. For NWMCFs except Tropospheric Ozone precursors:

$$\sum_{n\,=\,NWMCF\ source} E_n(t_o) \times RE_n$$

c. For Tropospheric Ozone:

$$\sum_{k=TOPr} \int_{t_0}^{t_F} E_k(t_o) \times \mu RF(t)\, dt$$

Where:

- t_F is the year in which RF is being calculated
- t_0 is the first year in the analysis timeframe
- $E(t_o)$ is the emissions of one source of a given species in year t_o, in tonnes
- RE is the radiative efficiency of the NWMCF
- µRF(t) is the unit RF for the climate forcer in mW/(m^2 Tg) in year t, calculated using Equations A.3-A.6

For each forcer, µRF (the RF resulting from the pulse emission of one million tonnes of a forcer) in Equation A.2 is quantified using Equation A.3 through Equation A.6. Quantification details are also included in the equations.

Equation A. 3. The RF resulting from the pulse emission of one million tonnes of CO_2 (i.e., the unit RF equation), from the IPCC Fifth Assessment Report.

$$\mu \boldsymbol{RF_{CO2}(t)} = \boldsymbol{RE_{CO2}} \times \left(\boldsymbol{a_0} + \left(\boldsymbol{a_1} \times \boldsymbol{e}^{-\frac{-t}{\tau_1}}\right) + \left(\boldsymbol{a_2} \times \boldsymbol{e}^{-\frac{-t}{\tau_2}}\right) + \left(\boldsymbol{a_3} \times \boldsymbol{e}^{-\frac{-t}{\tau_3}}\right)\right)$$

Where:

- t is the number of years after the pulse emission occurred
- RE_{CO2} is the radiative efficiency of CO_2, in mW/(m^2 Tg), which changes over time as the CO_2 concentration changes
- The default values for the atmospheric concentration equation parameters (a_0, a_1, τ_1, a_2, τ_2, a_3, τ_3) in Table A.1 are used unless more up-to-date values are available

A default value of 0.0017008 mW/(m^2 Tg) is used for RE_{CO2} unless more up-to-date and accurate values are available [IPCC AR6, Table 7.SM.7]. This value must be updated whenever possible to account for the impact of band saturation on radiative efficiency. The atmospheric decay equation from IPCC AR5 (Ri in Equation 8.SM.7 from IPCC AR5, §8.SM) is used as a default.

Equation A. 4. The RF resulting from the pulse emission of one million tonnes of a non-CO_2 GHG (i.e., the unit radiative forcing equation), from the IPCC Fifth Assessment Report.

$$\mu RF_{WMGHG}(t) = RE_{WMGHG} \times e^{-t/\tau}$$

Where:

- t is the number of years after the pulse emission occurred
- RE_{WMGHG} is the radiative efficiency of the WMGHG, in mW/(m^2 Tg), which changes over time as the WMGHG concentration changes. RE_{WMGHG} from the latest IPCC report is used as a default (Table A.2)
- τ is the average atmospheric lifetime of the non-CO_2 WMGHG, in years

Any radiative efficiency values that are converted into units of mW/(m^2 Tg) from W m^{-2} $ppbv^{-1}$ follow the requirements of *IPCC Fifth Assessment Report*, Chapter 8 Supplemental Material: "To convert RE values given per ppbv values to per kg, they must be multiplied by (MA/Mi)(10^9/TM) where MA is the mean molecular weight of air (28.97 kg $kmol^{-1}$), Mi is the molecular weight of species I and TM is the total mass of the atmosphere, 5.1352 x 10^{18} kg."

For methane, RE_{CH4} includes the following indirect effects that influence the radiative efficiency: formation of tropospheric ozone; effect on sulfate aerosols concentrations; effect on stratospheric water vapor; effect on nitrate aerosol concentrations; and from CO_2 formation (Shindell et al., 2009).

For non-CO_2 WMGHGs besides methane, τ from the latest IPCC reported is used as a default (Table A.2).

Equation A. 5. The RF resulting from the pulse emission of one million tonnes of a NWMCF with an atmospheric lifetime of less than one year (i.e., the unit radiative forcing equation).

$$\mu RF_{NWMCF}(t) = \begin{cases} \boldsymbol{RE_{NWMCF}\ when\ t < ARTMP} \\ \boldsymbol{0\ when\ t > ARTMP} \end{cases}$$

Where:

- t is the number of years after the pulse emission occurred
- ARTMP is the Atmospheric Residence Time Modeling Parameter, in units of time, which is equal or less than one year, and as a default one year
- RE_{NWMCF} is the radiative efficiency of the NWMCF, in mW/(m^2 Tg) [1)]

[1)] RE_{NWMCF} is evaluated as the average radiative forcing resulting from the pulse emission of one million tonnes of the NMWCF over the course of the ARTMP. If ARTMP is one year, then RE_{NWMCF} is averaged over one year (see Table A.3 default values for sulfur dioxide, and Table A.4 for default values for black and organic carbon for ARTMP values of one year).

Considerations for quantifying µRF for NWMCFs with atmospheric lifetime of less than one year:

- RE_{NWMCF} takes into account the fact that these NWMCFs are not evenly distributed in the global atmosphere and their impact varies regionally, and by source type.

- The following factors that affect the RF of these NWMCFs are considered:
  - Rate of emission, weather conditions, location, timing (season, hour of day), and altitude of emission source. Data used to characterize RF from NWMCFs are based on multiple years to minimize the effects of natural climate variability. This can be achieved by basing results upon average seasonal or average annual atmospheric concentrations of the NWMCFs.
  - For all aerosols, indirect effects are characterized to the extent possible. This can involve use of conservative estimates. Examples include the enhancement of cloud albedo by sulfate aerosols, and deposition of black carbon on ice, snow and other reflective surfaces.
  - Other factors that can affect the RF are considered if they have a material effect.
  - Estimates of RF by source are obtained from peer-reviewed published research.
- When assessing the contribution to RF from black carbon, organic carbon, and brown carbon:
  - Direct observations of RF, if available, serve as the basis of the forcing of these climate forcers. Model-based quantifications based solely on bottom-up emissions estimates are compared to direct observations before being used to calculate the result. RF derived from climate models based on bottom-up emissions estimates have been found in some studies to underestimate black carbon concentrations by 3- to 10-fold (Bond et al., 2013; Menon, et al., 2010).
  - The RF per ton of black carbon differs significantly based on the region of emission, due to latitudinal differences in solar radiation, regional differences in baseline clouds, vertical transport of black carbon, underlying albedo, and vegetation cover. Differences based on the region in which black carbon is emitted are taken into account.
  - Special care must be taken when including brown carbon, the composition of which can be highly variable; as such, an analysis should be done for each specific situation. In most cases, the positive forcing from brown carbon is similar in magnitude to the negative forcing from organic carbon (Feng et al., 2013; Chung et al., 2012). Accordingly, in the result, it can be assumed as a default that RF from co-emitted brown and organic carbon aerosols offset each other. This assumption is recorded.
  - The enhanced RF resulting from deposition on ice and snow is included.
  - Indirect effects on clouds, to the extent they are relevant and can be estimated, are included.
  - For all carbonaceous aerosol emissions, the type of combustion is factored into the overall quantification. (Black carbon emissions from fossil fuels are known to have different characteristics than black carbon emissions from open burning sources.)
- When assessing the contribution to RF from sulfate emissions, the following are included in the RF quantification:
  - The conversion rate of SO_2 emitted to sulfate and sulfite (SO_3^{2-}, SO_4^{2-}).
  - Regional washout rates and other meteorological factors affecting aerosol lifetime.
- Estimates of indirect radiative effects (i.e., cloud brightening effects).

Equation A. 6. Unit RF equation for a pulse emission of 1 million tonnes of a non-methane tropospheric ozone precursor.[5] *Based on the metric calculations described in Section 5 of Fry et al., (2012), with the land use term supplemented from Collins et al. (2010).*

$$\mu RF_{TOPr}(t) =$$

Tropospheric Ozone Effect(t) + Sulfate Effect(t) + Nitrate Effect(t) + Methane Effect (t) =

$$\left[TOPr_{O_3} + TOPr_{SO_4^{-2}} + TOPr_{NO_3^-}\right] + k \times \mu RF_{CH4}(t)$$

Where:

- t is the number of years after the pulse emission occurred
- Tropospheric Ozone Effect represents the direct RF increase from the formation of tropospheric ozone
- Sulfate Effect represents the perturbation of sulfate formation resulting from NOx reactions to break down these aerosols and is not relevant to precursors other than NOx
- Nitrate Effect represents the generation of ammonium nitrate aerosols (in regions of high ammonia abundance)
- Methane Effect represents the enhanced atmospheric decay of methane resulting from ozone oxidation (Collins et al., 2013)
- $TOPr_{O3}$, $TOPr_{SO4}$, $TOPr_{NO3}$, are the respective magnitude of the non-methane tropospheric ozone precursor's indirect effects on tropospheric ozone, sulfates, and nitrates
- k is a unitless value equal to the tonnes of methane oxidized per ton of TOPr emitted
- $\mu RF_{CH4}(t)$ is the RF of one million tonnes of methane t years after the pulse emission

In quantifying these radiative effects, climate models considering chemistry and dispersion must be used. If this is not practical, then these effects can be left out of the calculation. Default values for $TOPr_{O3}$, $TOPr_{SO4}$, $TOPr_{Ni}$, k, for NOx emissions from Table A.5 can be used, but the resulting effect on the uncertainty of final RF footprint results, which will be significant, should be considered.

Table A. 1. Default parameters for quantifying μRF for CO_2 in Equation A.3.

See Equation 8.SM.10 and Table 8.SM.10 in IPCC AR5 Working Group 1, Chapter 8 Supplemental Material

Parameter	*1st term*	*2nd term*	*3rd term*	*4th term*
Unitless exponential coefficient (a_i)	$a_0 = 0.2173$	$A_1 = 0.2240$	$A_2 = 0.2824$	$a_3 = 0.2763$
Time scale (τ_i) in years	Not applicable	$\tau_1 = 394.4$	$\tau_2 = 36.54$	$\tau_3 = 4.304$

Table A. 2. **Default Radiative Efficiencies (RE) and Average Atmospheric lifetimes for GHGs**

GHG	*RE mW/(m^2 Tg)*	*Average Atmospheric Lifetime τ*	*Data Source*
Methane (CH_4)	0.20	11.8 years	IPCC AR6 Table 7.SM.6 and calculation
Nitrous Oxide (N_2O)	0.358	109 years	IPCC AR6 Table 7.SM.6 and calculation
Sulfur Hexafluoride (SF_6)	21.8	1000 years	IPCC AR6 Table 7.SM.6 and calculation
HFC-134a	9.21	14 years	IPCC AR6 Table 7.SM.6 and calculation
Nitrogen Trifluoride (NF_3)	16.2	569 years	IPCC AR6 Table 7.SM.6 and calculation

Table A. 3. Default Radiative Efficiencies (RE) for sulfur dioxide emitted in four different regions

Forcer	*RE, mW/(m^2 Tg)* [1]	*Data Source*
Sulfur Dioxide (SO_2) from East Asia	-5.1	Collins et al. (2013) and Shindell et al. (2009)
SO_2 from Europe	-6.8	Collins et al. (2013) and Shindell et al. (2009)
SO_2 from North America	-6.8	Collins et al. (2013) and Shindell et al. (2009)
SO_2 from South Asia	-6.8	Collins et al. (2013) and Shindell et al. (2009)

NOTE: RE values in this table are from Table 1 of Collins et al. (2013), taken as identical to the AGWP-20 values (the Absolute Global Warming Potential, or AGWP, is the same over any time horizon for short-lived climate forcers, and the RE over one year is the same as the AGWP over a one year time horizon), but increased by 75% to account for the indirect effect of sulfate aerosols on clouds (the calculation approach used by Shindell et al. (2009) to estimate the indirect effect on clouds).

Table A. 4. Black carbon and organic carbon radiative default efficiency values, for different regions and source types. Includes both the direct and indirect effect from deposition on ice and snow.
Calculated using Table 1 of Bond (2011).

Region	*Black carbon RE, mW/(m^2 Tg)*	*Organic Carbon RE, mW/(m^2 Tg)*
Global average	71.6	-3.98
Energy-related sources		
Average energy	69.1	-2.61
Canada	74.1	-1.31
USA	62.9	-1.93
Central America	74.1	-3.30
South America	75.9	-3.05
Northern Africa	82.8	-3.61
Western Africa	77.2	-3.86
Eastern Africa	72.8	-4.23
Southern Africa	78.4	-4.86
OECD Europe	60.4	-1.99
Eastern Europe	65.4	-2.30
Former USSER	84.0	-1.87
Middle East	84.7	-3.61
South Asia	88.4	-5.04
East Asia	63.5	-1.62
Southeast Asia	61.0	-2.80
Oceania	64.1	-3.49
Japan	49.2	-0.87
Open burning-related emissions		
Average open burning	76.6	-4.61
Europe	89.0	-4.48
Northern Asia	128.2	-3.55
Southern Asia	90.3	-5.98
North America	117.7	-3.55
S/C America	85.9	-5.73
Africa	56.0	-3.80

NOTE: Black carbon and organic carbon specific forcing pulse values were converted to GWP20 values by dividing by 4 x 10^{-4} and then to AGWP-20 by multiplying with AGWP-20 of CO_2. As the AGWP-20 is identical to AGWP-1 for black carbon, this value was taken as the annual average radiative efficiency (Bond et al., 2011). Value is based on the highest SFP value for black carbon.

Table A. 5. Radiative efficiency and k values for different effects of NOx that can be used as a default.
Columns $TOPr_{O3}$ and K from Fry et al (2012); Column $TOPr_{Ni}$ from Collins et al. (2013)

	$TOPr_{O3}$ [1)]	$TOPr_{SO42-}$ [1)]	$TOPr_{NO3-}$ [2)]	*k*
East Asia	2.47	0.16	-2.0	-0.87
European Union	0.93	-0.37	-2.0	-0.56
North America	2.42	0.14	-2.0	-0.93
South Asia	4.28	-0.48	-2.0	-1.71
Averaged 4 regions	**2.14**	**-0.08**	**-2.0**	**-0.87**

[1)] $TOPr_{SO42-}$ and $TOPr_{O3}$ respectively characterize the effect of a NOx emission on the destruction or enhancement of sulfate aerosols and tropospheric ozone formation. To calculate these parameter values in the table, the 20-year AGWPs calculated from Table S2 (using the standard conversion of AGWP to GWP) of the Supplemental Material for *Fry et al. (2012)* was taken for these specific effects. The effects are short-lived and therefore the 20-year AGWP is the same as 1-year AGWP values, which are equivalent to the average one year for the radiative efficiency of methane's effect on these pollutants. Therefore, these values are numerically equivalent to the 20-year AGWP reported in Table S2 of *Fry et al. (2012).*

[2)] $TOPr_{Ni}$ is taken as -2.0×10^{-12} W m^{-2} kg^{-1}, using data reported in *Collins et al. (2013).*

The k values in Table A. 5. Radiative efficiency and k values for different effects of NOx that can be used as a default.are calculated from Table S2 of Fry, et al. (2012), by dividing the AGWP-20 of methane with the calculated AGWP-20 of the NOx methane effect in this table. These k values correspond approximately to the kilograms of methane destroyed by each kilogram of emitted NOx. See table below for examples.

Table A. 6 AGWP-20 and k values from Fry, et al. (2012)

	AGWP-20, methane, calculated	*AGWO-20, methane effect*	*K, unitless*
East Asia	2.55	-2.21	-0.87
European Union	2.55	-1.42	-0.56
North America	2.55	-2.36	-0.93
South Asia	2.55	-4.35	-1.71
4 Regions	2.55	-2.22	-0.87

A.4 Global Radiative Forcing Changes from Non-Emission Climate Forcers

Direct effects on surface reflectivity are considered – i.e., changes in the albedo resulting from land use changes, reflectivity of clouds (Equation A. 7. Calculating the RF from a change in albedo between tF and an earlier time t0). Indirect effects on surface reflectivity are quantified or estimated, provided they are expected to have a material effect on net RF results. If indirect effects would lead to an increase in RF, they are quantified to understand the total net RF change induced by the activity.

Equation A. 7. Calculating the RF from a change in albedo between t_F and an earlier time t_0 (included in $RF_{non\text{-}emission\ CF}$) (Lenton and Vaughan, 2009).

$$RF_{albedo\ change}(t_F, t_0) = -RF_{TOA} \times \mathcal{F}_a \times (\alpha_F - \alpha_0) \times \frac{A_{alb}}{A_{Ea}}$$

Where :

- t_f is the year in which RF is being calculated
- t_0 is the first year in the analysis timeframe
- RF_{TOA} is the downward solar radiation at the top of the atmosphere
- $\mathcal{F}_a$ is an atmospheric transmittance factor expressing the fraction of the radiation reflected from the surface that reaches the t top of the atmosphere
- $(\alpha_F - \alpha_0)$ is the change in surface albedo from t_0 to t_F
- A_{alb} is the albedo changed area
- A_{Ea} is the surface area of the Earth (510 million km^2)

In addition to albedo, $RF_{non\text{-}emission\ CF}$ may include factors such as thermal pollution and loss of evaporative cooling.

Direct and indirect changes to RF resulting from increased emittance of lower frequency radiation (i.e., Earth radiation) are also considered if they are material.

The effect on known feedback loops is considered, and their effect on RF is considered if they have a material effect.

A.5 Methods of Reporting Excess RF

The excess RF compared to the historical baseline can be described and reported in three ways (Table A.6). The RF, reported in watts per square meter, can also be reported as "Total Heat Level Increase" based on the excess heat absorbed across the total surface area of the Earth (510 million square kilometers).

Table A. 7. Three Approaches to Measuring and Reporting the Excess RF
As shown in the three rows, values scale up linearly.

Radiative Forcing (W/m^2)	***Radiative Forcing (CO_2fe)***	***Total Heat Rate Level Increase (Trillion Watts (TW))***
1	564×10^9	510
2	$1{,}128 \times 10^9$	1,020
3	$1{,}692 \times 10^9$	1,530

A.6 Regional High-Risk Zone Impact Assessment

Regional high-risk zones are regions where local climatic conditions are significantly altered from pre-industrial period conditions. Regional high-risk zones have distinct regional climate disruptions that are reflected in specific midpoints and endpoints.

Examples of altered conditions that would define regional high-risk zones include regions of the earth's surface experiencing:

- A sustained regional mean temperature anomaly significantly higher than the global temperature anomaly on a consistent basis (over at least 5 years) – see Figure A.1;
- Significant localized changes in the solar radiation or upward convective heat transfers, either positive or negative;
- Significant localized changes in the hydrological cycle (Ramanathan, 2008);
- Changes in regional atmospheric circulation patterns;
- Changes in seasonality of temperature and/or RF changes;
- High rates of sea level rise;
- Significant increases in wildfires induced from climate change;
- Surface dimming; and
- Effects on local snowpack, ice cover, or other albedo changes.

Figure A.1 shows the changes in regional variation in of global temperature anomalies over the earth's surface over a period of 140 years.

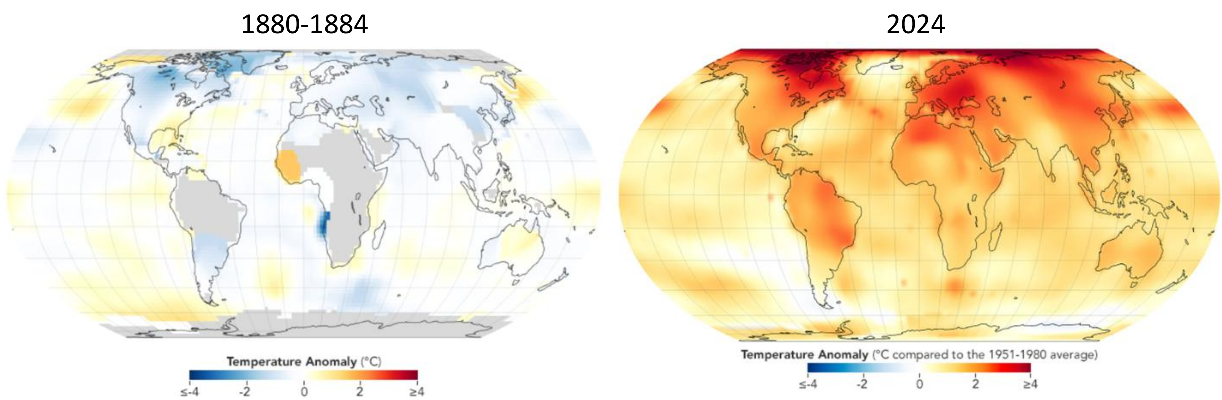

Figure A. 1 Regional variations in global temperature anomalies, 1880-2024

Source: https://earthobservatory.nasa.gov/world-of-change/global-temperatures

A.6.1 Identification of regional high-risk zones

The characteristics (e.g., spatial, temporal, severity) of regional high-risk zones are described. If identified, the following information is described regarding the high-risk zone, at a minimum:

- The cause-effect chain that has led to the regional high-risk zone. This includes a specific description of the observations and measurements related to the midpoints that characterize the regional high-risk zone. The main contributors to these midpoints are ascertained.
- The size, duration, seasonality, and periodicity of the key midpoint(s) for the regional high-risk zone.

The effect of emissions and/or activities are evaluated to determine if there are any linkages, intended or unintended, and positive or negative, to regional high-risk zones. Linkages involve any climate forcer emissions that transport into known regional high-risk zones that affect their magnitude, size, or severity, or activities that have an influence on the severity of the local regional high-risk zone, directly or indirectly.

For example, as a default, any project or organization that contributes positive RF emissions (e.g., aerosols, precursor pollutants) in the following regional high-risk zones can be considered to be linked to these regional high-risk zones, identified as the major brown cloud hot spots: East Asia, South Asia, Southeast Asia, Indonesia/Malaysia, South America, and Central Africa (Ramanathan et al., 2008). Another example would be activities occurring in the Arctic that could influence the local Arctic climate. Additional identification of linkage to regional high-risk zones is determined on a case-by-case basis.

A.6.2 Quantifying effects on regional high-risk zones (general parameters)

For any project or organization that is directly contributing to climate disruptions within a regional high-risk zone, the specific factors that are most relevant to the severity of the regional high-risk zone conditions should be identified. Careful consideration of the cause-effect chain is required to identify the underlying causes of the regional high-risk zone, which may be linked to regional-level activities, or to larger climatological patterns or feedback loops. The following effects should be quantified:

- The contribution of the project or organization activities to the key conditions that characterize the regional high-risk zone's severity; and
- The degree to which the project or organization's activities could reduce RF in the regional high-risk zone.

A.6.3 Quantifying effects on regional high-risk zones tied to black carbon pollution

Effects of black carbon pollution in several regional high-risk zones are well known (Ramanathan, 2008) and understood to be relevant for many organizations and projects. These impacts are relevant if the RF project or organization's activities are located in regions in or near these regional high-risk zones, and emit black carbon, nitrogen oxides, sulfur dioxide, carbon monoxide, volatile organic compounds (VOCs), or other pollutants contributing to these local regional high-risk zones.

Separate category indicator results are included for each regional high-risk zone relevant in the analysis scope. The category indicator addresses the local emissions of NWMCFs contributed to regional high-risk zone conditions.

Equation A. 8. Quantifying regional high-risk zone impacts tied to brown cloud pollution

Regional high-risk zone Impacts (tonnes black carbon equivalent) =

$$\sum_j \sum_i E_{NWMCF} \times M\text{-}CF_j$$

Where:

- E_{NWMCF} are emissions in tonnes, including black carbon, NOx, SO_2, and organic carbon contributing to the local regional high-risk zone.
- j is the total number of unit processes in the scope.
- i is the total number of aerosols and aerosol precursors emitted.
- M-CF is a regional midpoint characterization factor

M-CF characterizes the potential release of aerosol*s* and aerosol precursors and the equivalent mass of black carbon formed in the atmosphere that result in effects to climate in the regional high-risk zone.

To determine the regional impacts of a given climate forcers, regional dispersion and atmospheric chemistry modeling are used.

A.7 Data Quality and Uncertainty Considerations

When quantifying RF, different kinds of uncertainty and data quality should be taken into consideration and noted, such as:

- Atmospheric lifetimes of different species
- Radiative properties of different species
- Net RF from emissions of organic carbon from its short-wave/UV absorption (i.e., from brown carbon absorption).
- Uncertainty in quantifying biogenic emissions of N_2O and methane from agricultural systems
- Uncertainty in quantifying biogenic carbon uptake and retention from land-based projects/organizational activities (e.g., forestry, biofuels)
- Uncertainty in ocean and land carbon absorption
- Black carbon direct RF absorption
- NO_X conversion rates to tropospheric ozone, nitrate aerosols
- Indirect RF effects of ozone precursors – tropospheric ozone effect on methane, effects on carbon uptake by plants
- Magnitude of effect of methane on tropospheric ozone
- Effects of local meteorological conditions
- Effects of aerosol-cloud interactions
- Greenhouse gas concentration effect on RF
- Aerosol-cloud interactions (affecting aerosol and precursor emissions)
- Variations in WMGHG Radiative Efficiency due to uncertain projections of WMGHG concentration
- Differences in the way the longwave and shortwave radiative forcing impact the atmosphere and surface
- Aggregation of RF across different forcers or time periods
- Future scenario information, in particular at smaller spatial scales or project level
- Historical emissions in the quantification RF

- Carbon cycle feedbacks
- Climate feedback

Annex B

Radiative Forcing Stabilization Targets

B.1 Determining RF Stabilization Targets

Establishment of RF reduction goals and plans of action is contingent upon the RF stabilization target adopted. Such a target is necessary for an organization to identify the project types it prioritizes for implementation. The RF stabilization target includes a specific target RF value (i.e., defined in W/m^2) for specific target years, based upon goals set by UNFCCC or other entities, for example, including but not limited to 2030.

Equation B.1 describes how to quantify a global RF stabilization target associated with a specific maximum global surface temperature (GST) anomaly target.

Equation B. 1. Quantifying a global RF stabilization target associated with a maximum GST anomaly target.

$$\mathrm{RF_{target}} = \frac{\mathrm{Temperature_{target}}}{\mathrm{Climate\ Sensitivity}}$$

Where:

- RF_{target} is the global RF stabilization target, in Watts per square meter.
- $Temperature_{target}$ is the maximum temperature anomaly target, in °C.
- Climate sensitivity is the equilibrium climate sensitivity, in °C per W/m^2

[Source: IPCC Fifth Assessment Report]

The equilibrium climate sensitivity value used in Equation B.1 is that which is published by the IPCC in the latest relevant Assessment Report. In the 2018 IPCC SR1.5 report, +1.9 W/m^2 is identified as the RF anomaly limit to maintain the global mean temperature anomaly below +1.5°C. The equilibrium climate sensitivity which is used is 0.79°C per W/m^2.

National governmental organizations can select a RF stabilization target and the point in time at which this target will be reached and at least sustained that align with their organizational goals (e.g., aligning with the Paris Agreement), and also provide the justification for such choices.

B.2 Quantifying RF Reduction Goals

Organizations will choose which time periods of RF reduction are of the highest priority, and therefore which RF reduction goals will be set. Any prioritization will be stated, and the justification provided.

An organization or project's RF reduction goals are understood in the context of the RF reduction needed to achieve a given RF stabilization target. Specific targets and RF reduction goals are refined over time to reflect ongoing scientific refinements in climate sensitivity and emissions trajectories. Equation B.2 supports the updating of global RF reduction goals on a regular basis.

The amount of RF reduction needed in a given year is be quantified by subtracting the RF_{target} in Equation B.1 from the reasonable business-as-usual RF level in each year using Equation B.2.

Equation B. 2. Quantifying a global RF reduction objective associated with an RF stabilization target linked to maximum GST anomaly goals.

$$\Delta RF(t) = RF_{bau}(t) - RF_{target}$$

Where:

- t is the year
- $\Delta RF(t)$ is the reduction in RF required in year t
- RF_{target} is the RF stabilization target calculated according to Equation B.1
- $RF_{bau}(t)$ is the reasonable business-as-usual (bau) RF level in year t

The reasonable business-as-usual RF level is based upon peer-reviewed projections from major climate models (e.g., as noted in AR5).

NOTE: Four RCPs were modeled in the IPCC Fifth Assessment Report: RCP2.6, RCP4.5, RCP6.0, and RCP8.5. Under RCP2.6, RF peaks at approximately 3 W/m² before 2100 and then declines to stabilize at about +2.6 W/m². RCP4.5 and RCP6.0 were two intermediate stabilization pathways in which RF is stabilized at approximately +4.5 W/m² and +6.0 W/m² until 2100. Under RCP8.5, RF was projected to exceed +8.5 W/m² by 2100 and continue to rise for some amount of time.

Table B. 1. RF reductions required using the global RF reduction objectives associated with maximum global mean temperature anomaly goals of 0.0°C and 1.5°C. RF reductions are compared to RCP8.5. All RF reductions are calculated using Equation B. 1. Quantifying a global RF stabilization target associated with a maximum GST anomaly target.Equation B. 2. Quantifying a global RF reduction objective associated with an RF stabilization target linked to maximum GST anomaly goals.

GST Maximum	*0°C*	*1.5°C*	*1.5°C*
RF Stabilization Target	*0.0 W/m²*	*1.5 W/m² (conservatively high equilibrium climate sensitivity of 1.0°C per W/m²)*	*1.9 W/m² (equilibrium climate sensitivity of 0.79°C per W/m²)*
Year	**RF reduction required**	**RF reduction required**	**RF reduction required**
2025	2.9	1.4	1.0
2030	3.3	1.8	1.4
2035	3.6	2.1	1.7
2040	3.9	2.4	2.0
2045	4.3	2.8	2.4
2050	4.7	3.2	2.8
2055	5.1	3.6	3.2
2060	5.4	3.9	3.5
2065	5.8	4.3	3.9
2070	6.2	4.7	4.3
2075	6.5	5.0	4.6
2080	6.9	5.4	5.0
2085	7.3	5.8	5.4
2090	7.6	6.1	5.7

2095	7.9	6.4	6.0
2100	8.3	6.8	6.4

Figure B. 1 Illustrative example showing the RF reduction required to maintain the global meanprovides an example that illustrates the level of global RF reduction needed to achieve two different RF stabilization goals relative to the IPCC AR5 RCP8.5 scenario: 1) to prevent the GST anomaly from crossing +1.5°C; and 2) to achieve an even more aggressive goal of lowering GST anomaly back to the 2012 level of +0.8°C (e.g., that might be required for high-risk zones). If a more ambitious target of no more than 0.5°C is set, then this would require a corollary RF target of 0.5 W/m^2 or less.

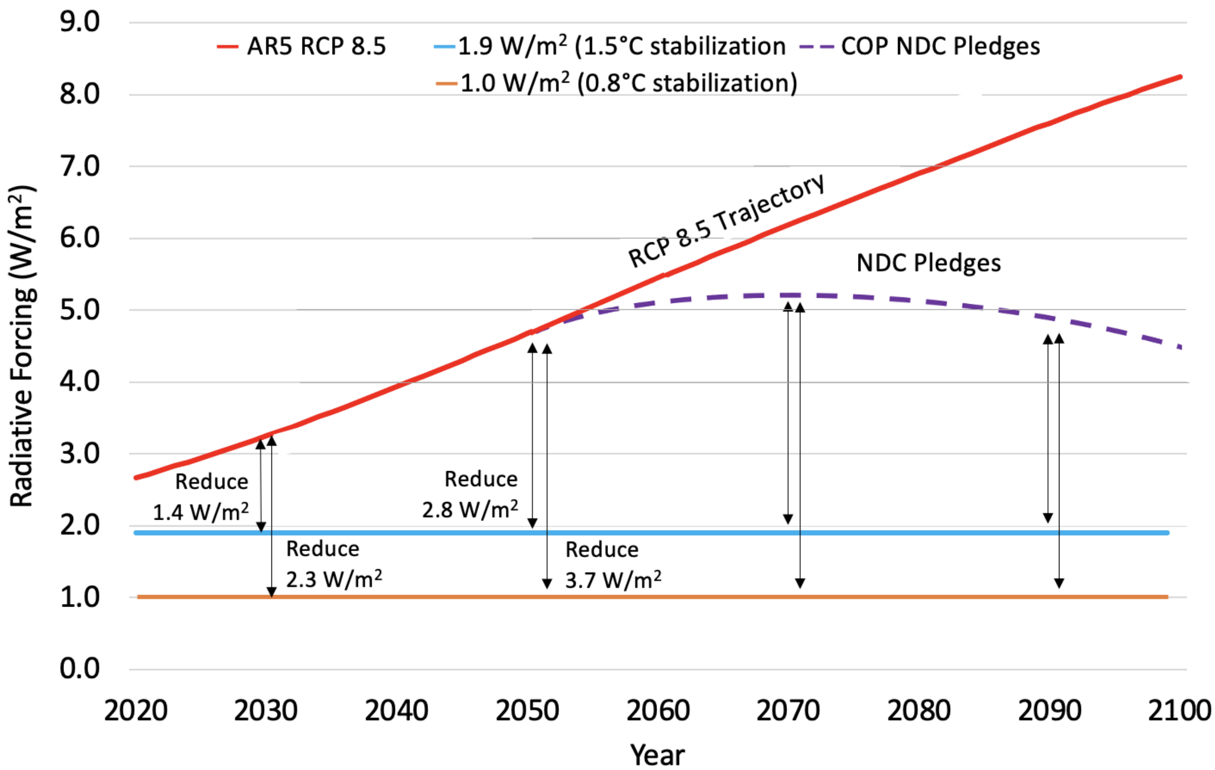

Figure B. 1 Illustrative example showing the RF reduction required to maintain the global mean temperature at +1.5°C (i.e., 1.9 W/m^2) or below +0.8°C (i.e., 1.0 W/m^2) when compared to RCP 8.5. This figure assumes that substantial effects of 2nd round of NDCs pledged in 2021 begin to be seen at 2050. While there is uncertainty regarding future RF levels included in this figure, the most widely accepted estimates by the IPCC in its Representative Concentration Pathways (RCPs) scenarios project a rise to about +3.0 W/m^2 by 2030 –a rate that, if sustained, would eventually lead to an increase in average global temperature to over +2.0°C. As described in the IPCC SR1.5, maintaining RF at +1.9 W/m^2 will provide a 50% likelihood of stabilization of the GST anomaly at about +1.5°C. (Source: IPCC, 2018)

B.3 Working Toward Global and Regional RF Stabilization

B.3.1 Global RF Reduction Plans

Organizations develop global RF reduction plans focused on:

- RF stabilization targets and global RF reduction goals for specific years, including 2030; and
- A set of RF reduction projects sufficient in scale to achieve stated RF reduction goals.

B.3.2 Regional RF Reduction Plans

Organizations can also establish RF reduction plans for specific regions facing extreme near-term risks from climate change. Such plans:

- Are regional in scope, identifying the nature of the particular risk and the means by which this risk is monitored;
- Include quantified goal(s) in each high risk-area (e.g., restoration of regional surface temperature to 1950 levels, or reduction in extreme heat wave incidence by 50%);
- Include RF reduction projects sufficient in scale and timeliness to reduce regional climate-induced impacts within the very near-term (5-20 years);
- Include timelines for implementation and RF reduction achievement milestones;
- Rely on projects with no significant climate or other trade-offs that cannot be mitigated;
- Provide documentation, including a listing of data, climate models, and assumptions used to generate the list of RF reductions and the RF reduction plan; and
- Are reviewed by independent experts and stakeholders.

NOTE: Examples of high-risk zones include: regions at extreme risk of flooding from rising sea levels, such as small island nations and many coastal cities; regions at risk of temperature spikes and mean temperatures far in excess of GST, such as parts of the western US; regions at risk of major food or water insecurity due to drought or other food source imperilment, such as parts of India and sub-Saharan Africa; and regions subject to major ecosystem alterations, such as the Arctic.

Annex C

A Life-Cycle Assessment View of the Radiative Forcing Metric

LCA involves analysis of the system of physical, chemical and biological processes for a given impact category, linking the life cycle inventory analysis results to category indicators and to category endpoints – i.e., the "environmental mechanism." The cause-effect biophysical pathway from stressor to midpoint(s) and final endpoint(s) is modeled as a "stressor-effects network." (Each point along this pathway is referred to as a "node." Midpoint nodes represent observed chemical, physical, radiological or biological impacts along this pathway.)

The stressor-effects network for global climate change is modeled in Table C. 1. Stressor-effect network for global climate change Quantification of climate change impacts requires selection of a category indicator from the node in the stressor-effect network that best reflects the scale, duration, severity and potential reversibility of climate change endpoints. This process ensures that the quantification metric is placed at the "critical control point" that best supports prioritization of RF reduction actions with the greatest chance of mitigating, or even reversing, endpoints.

Table C. 1. Stressor-effect network for global climate change

Node	*Nodal Description Characterization*	*Comments*
1. Initial Releases (Stressors)	• Current emissions of well-mixed climate forcers, non-well-mixed climate forcers (particulates, aerosols), and negative climate forcers (e.g., sulfate aerosols) • Conversion of climate precursor emissions into climate forcers (e.g., NOx into Tropospheric Ozone)	• No reflection of the scale of emission reductions required to mitigate climate change endpoints • Does not include legacy GHGs and the climate impacts they continue to cause • No ability to track which activities lead to relevant radiative effects • Does not account for sequestration of carbon with partial release (e.g., soil carbon stocks) • Quantified link to adverse changes in climate change endpoints cannot be established
2. Increasing Concentrations (Midpoint)	• Increase in atmospheric concentration of well-mixed climate forcers from current and past emissions • Steady-state concentrations of non-well-mixed climate forcers from continuous and episodic emissions (e.g., from wildfires and from daily cooking and heating fires using wood and dung by hundreds of millions of people) • Increase in indirect non-emissions related climate forcers, such as albedo changes from land use alterations, increased exposure of dark land and sea surfaces as snow/ice cover retreat, reduced albedo of snow/ice from black carbon deposition, re-releases of stored heat from oceanic oscillations (e.g., El Niño, Pacific Decadal Oscillation)	

3. Changes in Radiative Forcing (Midpoint)	• Increase in net global RF from the combination of various climate forcers • Global RF levels are on a trajectory to reach +3 W/m^2 by 2030, +5 W/m^2 by 2055 and +8.5 W/m^2 by 2100.	• As a direct measure of the increase since pre-industrial times of the excess RF in the Earth climate system, RF is a leading indicator of climate change endpoints • Relatively high accuracy and precision in linking emissions to RF is possible • RF is essential metric for understanding the climate impacts from non-emissions related activities that lead to climate changes (e.g., albedo changes from land use alterations; reduced snow cover from black carbon deposition; enhanced sunlight absorption in seawater from ship icebreakers in the springtime Arctic) • RF increases can be projected with high confidence
4. Change in Earth Energy Imbalance (Midpoint)	• The Earth Energy Imbalance (EEI) increased from approximately 0.5 W/m^2 to >1.0 W/m^2 in one decade between 2008 and 2018	• The change in EEI reported is accurate even though the baseline has degrees of uncertainty • Emission reduction projects alone do not have the potential to alter or slow down the rate of increase in EEI by or before 2030 • Direct heat reduction projects focused on enhancing the release of excess Earth radiation into space are now urgently needed to hold EEI below 1.0 W/m^2
5. Changes in climate and circulation patterns (Midpoint)	• Intensification of Pacific Ocean heat oscillations (e.g., El Niño, Pacific Decadal Oscillation) and Siberian methane hydrate pulse (5,000 billion tons CO_2fe) • Conversion of the Arctic Oscillation permanently into the negative phase • Closing of Antarctic Ozone Hole (reduced intensification of Antarctic vortex) • Local temperature changes, rainfall pattern changes, extreme heat instances, increased ocean temperatures, ocean deoxygenation	• Mitigation projects now need to focus on reducing the total net increase in retained heat within the tropical circulation system, and cooling oceans • Evidence of tropical circulation system expansion is seen, for example, in the extreme drought conditions now expanding on both sides of the equator at the same latitude (Brazil, Western US) • Direct heat reduction projects have the potential to measurably reduce extreme hot spots within the region impacted by tropical circulation system but lack the scope to alter the overall increase in the heat within this circulation • The Arctic circulation system has been greatly impacted, disrupting the normal oscillation between positive and negative phases. The lack of a positive vortex (positive phase) has increased the seepage of cold fronts into the lower latitudes. The net effect has been a rapid increase in the warming of the Arctic region, and more severe winter storms in the lower latitudes.

		• It is technically feasible to restore the positive phase of the Arctic circulation using an extract of sea salt
6. Impacts (Endpoints)	• Exponential increases in ecosystem and human health impacts (e.g., coral bleaching, super typhoons and hurricanes, wildfires, droughts, sea level rises, climate refugees, diseases, species extinctions, ocean acidification)	
7. Changes in GST and RMT Equilibrium (Endpoint)	• After decades of increased RF, GST equilibrates to higher levels • Changes in regional mean temperatures (RMT) and regional amplification effects	• GST is a lagging indicator of adverse climate change. By the time certain temperature levels are reached, significant endpoints will already have occurred and may be "locked in," while further alterations will be unavoidable. • Linking of any one emission source or activity to GST or RMT changes has a higher level of uncertainty than earlier nodes. • Projections of GST and RMT increases (averaged over decades) and temperature spikes (e.g., from El Niño and Pacific Decadal Oscillation changes) are highly uncertain due to natural variability, ocean and atmosphere circulation patterns, and other considerations

The critical control point for global climate stabilization is Node 3 – i.e., changes in RF. This node has the elements needed to support climate stabilization decision-making, and was the basis of the IPCC Representative Concentration Pathway (RCP) scenario modeling in AR5 and SR 1.5, and reinforced in AR6. It is the basis of the RF climate accounting metrics in this document.

Annex D

Rationale for the Calculation of Carbon Dioxide Forcing Equivalents

Carbon dioxide equivalent (CO_2e) has long been recognized as the "unit for comparing the radiative forcing of a *GHG* … to that of carbon dioxide" [ISO-14064-1 (2018)]. Conventional carbon footprints, which focus on annual GHG emissions, are reported in CO_2e in order to be able to provide an aggregated result for the user's understanding and utility. The basic equation for calculating CO_2e multiplies the mass of a given GHG by its global warming potential (i.e., its relative radiative forcing over a specified time horizon), measured in watts per square meter (W/m^2).

As noted earlier, one hundred years has been the most frequently used time horizon, though the IPCC has cautioned: "There is no scientific argument for selecting 100 years compared with other choices. The choice of time horizon is a value judgement because it depends on the relative weight assigned to effects at different times" (IPCC AR5 WGI 8.7.1.2 pp.7 11-712). Forward looking carbon footprints that use CO_2e (100) frequently account for less than 5% of the total historical plus future RF footprint because they are limited to annual emissions of the GHGs, and omit the accumulated build of these long-lived GHGs.

Similar to conventional carbon footprints, RF footprints are reported in watts per square meter (W/m^2), and may additionally be reported in units of carbon dioxide forcing equivalents (CO_2fe) or joules (J) to provide an aggregated result for the user's understanding and utility. The equation for calculating CO_2fe is a straightforward conversion of the radiative forcing of a given amount of specific climate forcer compared to CO_2, measured in watts per square meter (W/m^2). Taking heed of the IPCC's statements regarding time horizons, RF footprints are calculated over multiple timeframes of analysis (not just 100 years) to ensure that near-term, medium-term and longer-term implications are understood.

In both cases, the normalization is based on highly accurate measurements of CO_2's radiative efficiency, as published by the IPCC. Thus, CO_2e is essentially a subset of CO_2fe. In essence, CO_2fe provides broader applicability, both in terms of the range of climate forcers that are included, and in terms of recommended timeframes of analysis.

Given that W/m^2 is the underlying metric for both CO_2e and CO_2fe, one might question why carbon footprints and RF footprints should not solely be represented in W/m^2. There are at least two reasons to use CO_2 as the basis of an equivalency, rather than only report results in raw units of W/m^2:

- The scientific and user communities have long recognized the importance of providing a unit of measure that can be easily understood by users. Since carbon dioxide is the most prevalent anthropogenic climate forcer on Earth, it was selected as the common index against which such an equivalency could be established. In addition, since carbon dioxide has the weakest radiative forcing ton-for-ton basis of anthropogenic climate forcers, the relative RF of any GHG or other climate forcer can be represented in relation to CO_2 as an integer.
- W/m^2 is the global average radiative forcing over every square meter of the earth (510 trillion square meters). No one organization can affect the climate on that scale. Many organizations and project developers and implementation partners using the RF protocol would likely be working

with results in the range of <0.000001 W/m^2. Thus, conversion to a more user-friendly unit is desirable.

The use of W/m^2, J, and CO_2fe and multiple timeframes of analysis benefit of the user community in several ways.

- W/m^2, J, and CO_2fe are applicable to all anthropogenic vectors affecting the climate system, including short-lived climate forcers and non-emission sources of radiative forcing, such as changes in albedo.
- Calculating W/m^2,J , and CO_2fe over multiple timeframes of analysis provides transparency into the near-term and long-term implications of any mitigation option.
- Reporting based exclusively on the 100-year time horizon has led to confusion among some key policymakers and decisionmakers as to methane's much higher RF impacts relative to CO_2 over shorter-term timeframes. Methane has a positive RF effect 82 times that of carbon dioxide over 20 years (AR6), and up to about 150 times during the initial year of release. Given that methane concentrations in the atmosphere are on the rise, focusing on the near-term radiative forcing effects and near-term mitigation is crucial. Calculating W/m^2 and CO_2fe over multiple timeframes accomplishes this goal.
- Similarly, when amortized over 100 years, CO_2e estimates have placed the value of black carbon mitigation at about 800-times CO_2 (IPCC AR5, Table 8.A.6), with a great deal of uncertainty. Yet while in the atmosphere, black carbon is many thousands of times more potent, ton per ton, than CO_2, and its concentration in the atmosphere is continuing to rise. Calculating W/m^2 and CO_2fe during the year of emission addresses this issue.
- Albedo changes, a major driver of climate change, are integrated under RF protocols. The loss of albedo is one of the largest unreported contributors to increased RF.
- RF inventories and footprints calculated using W/m^2 , J, and CO_2fe include the accumulated build-up of well-mixed GHGs, rather than focusing on annual emissions only. The legacy GHGs can account for as much as 90% of the current radiative forcing contribution from some entities. This feature is significant for developing countries burdened with combatting climate change in large part due to this accumulated build-up from the industrialized economies. RF footprints provide a fair and balanced view of shared responsibilities.
- Since W/m^2, J, and CO_2fe provide instantaneous measures of RF at a given point in time, they provide transparency into the timing of climate impacts, and support recognition of the rapid changes occurring on the ground now.
- W/m^2, J, and CO_2fe allow for accurate tracking and quantification of the changing marginal radiative efficiency of CO_2. Reductions in CO_2's radiative efficiency means that CO_2 emissions reductions in 2100 will cause about 60% less forcing per unit mass in 2020.
- RF footprints consider CO_2 based upon its radiative efficiency times its atmospheric lifetime, reflecting its true radiative effect on the atmosphere over time. The W/m^2 and CO_2fe results represented on the RF footprint can demonstrate the added RF reduction potential from mitigation of this CO_2 over long-time horizons, by demonstrating that a reduction in CO_2 emissions today leads to an RF benefit far into the future.
- Use of W/m^2 and CO_2fe can pave the way for new, cost-effective avenues for many developing economies to play a meaningful role in climate solutions, while enjoying simultaneous co-benefits such as reduced air pollution. This will serve the overall global fight against climate change, providing real, near-term market value for such efforts.
- W/m^2 can further be converted into terajoules over an annual basis using the surface area of the Earth for improved comprehension.

Annex E

LCA Framework for Co-Benefit and Trade-Off Assessment

The RF Protocol includes general guidance for conducting an analysis of the potential climate, environmental, human health, or food security co-benefits and trade-offs associated with an RF project that mitigates or otherwise results in a reduction in RF. This Annex provides additional information pertaining to the analysis of climate, environmental and human health impacts.

E.1 Goal and Purpose

RF projects can have corollary, and oftentimes unintended, consequences. As a result, it is important that any RF project under consideration be subjected to trade-off/co-benefit analysis – i.e., evaluated for its potential consequences, which can be either co-benefits (beneficial impacts) or trade-offs (adverse impacts). Use of a comprehensive assessment approach ensures that such projects are evaluated in a consistent manner before funding and implementation.

This analysis is applicable to all RF project options considered for implementation within a given RF reduction plan as part of the plan documentation, whether or not co-benefits or trade-offs are identified, and whether or not such options are ultimately implemented. Such analyses are also helpful in determining whether specific RF reduction plans are aligned with larger efforts to reduce RF levels sufficiently to stabilize temperatures below set targets (e.g., reducing RF levels by at least -1.4 W/m^2 by 2030 to achieve the UNFCCC goal of holding GST below 1.5°C). Since most RF project options will have at least some measurable trade-offs, the development of an overall roadmap will involve value judgments in selecting a given portfolio of options.

E.2 Characterization of Environmental Relevance

Life cycle assessment (LCA) provides the framework for this analysis, including the “environmental relevance” characterization parameters described in the ISO 14044 standard. These parameters include spatial and temporal characterization, severity characterization, and characterization of the reversibility of impacts. Such environmental characterization produces results that most closely reflect conditions on the ground, rather than being limited to impact “potentials” that might or might not reflect actual environmental conditions. Additionally, such methods will not only address flow and process related impact categories, but also those impact categories linked to non-process related impacts such as land use and displacement impacts (SCS, 2023).

Both direct and indirect trade-offs, both upstream and downstream, are included in this analysis. For instance, for regional electricity grids used to power EV vehicles, hazardous wastes produced from the grid include nuclear wastes and toxic heavy metals that require long term storage. Trade-off analysis includes all aspects of production, distribution, use and deposal (e.g., end-of-life issues surrounding EV vehicle batteries).

All trade-offs and co-benefits that affect UN Sustainable Development Goals are included. Projects are implemented with the precautionary principle in mind, considering environmental, human health, and social effects resulting from an activity.

For some UN SDGs and impacts, there may be tradeoffs, while for others, there may be co-benefits, all of which are transparently reported and understood.

E.3 Mitigation Options Including Trade-Off and Co-Benefits Assessment

As described in the protocol, RF projects are evaluated first for their Radiative Forcing Reduction Potential (RFRP). Once the RFRP is established, then proposed RF projects are analyzed for co-benefits and trade-offs. An example of a co-benefit is the reduction of tropospheric ozone precursors, which could also result in lower levels of smog-related air pollution. An example of a trade-off is the obstruction of a wildlife corridor associated with the construction of a renewable energy facility.

Based on this analysis, proposed projects will fall into one of four hierarchical categories.

- Positive RFRP, co-benefits, no trade-offs
- Positive RFRP, co-benefits and trade-offs
- Positive RFRP, trade-offs, no co-benefits
- Negative RFRP – i.e., climate trade-offs that exceed the RFRP of the project

Only those RF projects with positive RFRP should be pursued. Nonetheless, it is also valuable to document proposed RF projects found to have negative RFRP, including where in the life cycle such trade-offs exist, so that future consideration can be given to means to reduce or eliminate such trade-offs (e.g., new technology, siting options).

Most RF projects will have some trade-offs. Additionally, since most potential co-benefits will be projected based on estimates of future RF reduction, values may inherently have high degrees of uncertainty.

The use of environmentally relevant category indicators in the trade-off analysis provides an analytic platform to determine if measurable levels of impacts are occurring. The trade-off analysis is conducted by unit operation on an iterative basis using sensitivity analysis, threshold assessment and/or site-specific direct observations. Even after conducting a full iterative analysis, it is important to align the use of thresholds with established precautionary principles relevant to that impact category. If relevant, peer review and public stakeholder comments should be considered and addressed.

Annex F

Applying the RF Protocol to Analysis of a Brick Kiln Project

One promising project category for black carbon mitigation is the retrofit of traditional brick kilns in Asia, Africa, and Latin America. A pilot project focused on kiln retrofit is presented below.

This example, in which the RF Protocol is applied to the analysis of a specific project, is provided here for illustrative purposes. Further data collection and refinement is anticipated before the project would be ready for full peer review.

F.1 Project Overview

Scenarios. The RF Protocol was used to evaluate and compare the RF reduction potential, co-benefits and trade-offs for the retrofit of traditional brick kilns, based on three scenarios. Life cycle assessment (LCA) impact category results are presented for:

- a traditional straight-line Fixed Chimney Bull's Trench Kiln (FCBTK) that uses coal as a fuel (**Scenario 1**, the baseline scenario);
- a zigzag kiln that uses coal as fuel (**Scenario 2**, retrofit option 1); and
- a zigzag kiln that uses pellets made of rice husks as fuel (**Scenario 3**, retrofit option 2).

Brick Kiln Site. Results were calculated for one hypothetically retrofitted brick kiln Nepal. Using these results, the results for the retrofit of 40,000 traditional kilns were also calculated, based on the number of kilns that the World Bank estimates could be retrofitted in India (Eil et al., 2020).

Scope and Boundaries. The scope of the study was gate-to-gate (i.e., Scope 1 and 2), including the bricks firing process, and for Scenario 3, the pelletization process and avoided emissions from the open burning of agricultural waste. System boundaries included all relevant impacts associated with firing the bricks. Other upstream stages (e.g., material mining, brick prepping, storage, fuel transportation) as well as downstream stages (e.g., brick transportation, use and end-of-life) were assumed to be the same or very similar for each pathway, and as a result were excluded since they would not affect the comparison.

Functional Unit. The functional unit is the quantitative reference point of an LCA, which serves the purpose of providing a common basis for calculating environmental impacts. All the environmental impacts occurring across the life cycle of a product are analyzed and quantified in relation to the function of the product. In these modeling results, the typical brick kiln's annual production amount was assumed to be 6,000,000 bricks weighing 2.5 kg each. LCA results were calculated for this annual production; results from the three scenarios were compared for the retrofit of one kiln and 40,000 kilns, with appropriately scaled production amounts.

Impact Categories. Estimates were calculated for six core impact categories (Table F.1): non-renewable energy use, regional acidification, smog, soot ($PM_{2.5}$), accumulated ocean acidification, and the annual RF inventory and footprint.

Table F. 1 Relevant LCA Impact Groups and Impact Categories

IMPACT GROUP	IMPACT CATEGORIES
Resource Depletion	Non-Renewable Energy Use
Impacts from Emissions to Airsheds	Regional Acidification
	Smog
	Soot ($PM_{2.5}$)
Impacts from Emissions to Water	Accumulated Ocean Acidification
Climate Change Impacts	Annual RF Inventory and Footprint

It is important to note that several other impact categories may be relevant, such as hazardous air emissions, ecotoxicity, and water use. However, since no data were available to quantify those impacts, they could not be included.

F.2 Data

In general, the objective was to use data of sufficient quality to reliably quantify the differences in the three scenarios. For this study, certain data were obtained from a project developer who has previously retrofitted brick kilns from straight-line to zigzag.

Table F.2 below summarizes the specific types of data collected, and their sources.

Table F. 2 Data points used for LCA impact categories calculation and their sources

DATA COLLECTED	SOURCE
Bricks weight	Project developer
Production capacity (Sc. 1, 2 & 3)	Project developer
Emission factors CO_2 and SO_2 (Sc. 1 & 2)	Rajarathnam et al. (2014)
Particulate matter (Sc. 1 & 2)	Rajarathnam et al. (2014)
Black carbon/particulate matter ratio (Sc. 1 & 2)	Nepal et al. (2019)
Energy use per kg of brick (Sc. 1, 2 & 3)	Project developer
Organic Carbon (Sc. 1 & 2)	Weyant et al. (2014)
Emission factors pellet burning[(a)] (Sc. 3)	Fachinger et al. (2017)
Emission factors pelletization process (Sc. 3) [(b)]	Calculations based on multiple sources[6] [7] [8] [9] [10] [11]

[6] Pradhan et al. (2019)
[7] Haase et al. (2010)
[8] Pantaleo et al. (2020)
[9] Hunsberger et al.(2014)
[10] Sgarbossa et al. (2020)
[11] Treyer et al.(2016)

Emission factors open burning (paddy stalk)	Das et al. (2020)
Location	Project developer
Air quality (Soot and Ozone) [(c)] (Sc. 1, 2 & 3)	World Air Quality Index project[12]

[(a)] Burned biomass is considered CO_2 neutral. Woody pellets were used as proxy.
[(b)] Several pelletization operations were considered and a conservative value was used.
[(c)]Muzaffarpur Collectorate, Muzaffarpur, India was taken as a proxy.

F.3. Methodology

The study was conducted in accordance with the RF Protocol, and the impact category results were calculated based on data compiled for various resources and emissions.

To calculate results for each category, two characterization factors were applied: Stressor Characterization Factors (S-CF), which represent the relative potency of individual stressors that contribute to a common endpoint, and Midpoint Characterization Factors (M-CF), which characterize the temporal nature, spatial extent, severity, and reversibility of impacts on specific midpoints or endpoints. Characterization factors for each impact categories are described below.

To evaluate the co-benefits and trade-offs of Scenarios 2 and 3 against Scenario 1, Project Equation 1 was used. "Co-benefits" refers to reduced adverse impact category results (i.e., positive impact %), while "trade-offs" are increased adverse impact category results (i.e., negative impact %).

Equation F. 1. Co-benefits and trade-offs calculation

$$Impact\ \% = \left(1 - \frac{Scenario\ 2\ or\ 3\ impact}{Scenario\ 1\ impact}\right) \cdot 100$$

- ***Energy Resource Depletion***
  Based on the production and the energy intensity range reported by the project developer, and the type of energy source used by brick kilns, the energy calculations were conducted using the S-CF factors listed in Table F.3. The specific energy density per brick varies from technology to technology. For traditional brick kilns, it ranges from 1.5 to 1.8 MJ per kg, while for zigzag kilns, the energy consumption is 0.8 to 1.0 MJ per kg. The largest value for zigzag was used, and the smallest value for straight-line was used, in order to ensure that the differential calculated was conservatively small. For Scenario 3, there was only negligible energy resource depletion because the energy is not generated from fossil or mined fuels. This category does not have an M-CF.

[12] Air Quality Historical Data Platform, (2019). Muzaffarpur Collectorate, Muzaffarpur, India Air Pollution: Real-time Air Quality Index (AQI). [online] Available at: https://aqicn.org/city/india/muzaffarpur/muzaffarpur-collectorate

Table F. 3. Energy Resource Depletion S-CFs

Energy source	*Type of kiln*	*Energy Density (MJ per kg brick)*
Coal	Straight-line	1.5
Coal	Zigzag	1
Biomass Pellets	Zigzag	Negligible

- ***Regional Acidification***

  Regional acidification is calculated in units of equivalent mass of sulfur dioxide (SO_2e), which varies among emissions. SO_2 from brick kilns causes regional acidification, with an S-CF of one (1 kg SO_2e / 1 kg of emission).[13]

  The deposition of acidifying compounds in sensitive regions was estimated based on a Regional Acidification Map developed in 2011 based on the Harmonized World Soil Database.[14] Dispersion modeling was not used, but rather, an estimation based on the location of Nepal, in an area with soil PH lower than 6.5, making it an acid sensitive area (see Figure F.1 below). Thus, the M-CF equals one. While dispersion modeling will provide a more precise calculation of acid deposition and may change the M-CF, this dispersion plume will be identical between the two kilns, and so use of more precise dispersion modeling would not affect the comparison between straight-line and zigzag kilns.

[13] NOx also contributes to acidification; however not enough data were found to include it in the calculation.
[14] Regional Acidification Map developed by SCS Global Services based on Food and Agriculture Organization of the United Nations, Harmonized World Soil Database v 1.2. [online] available at: http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/

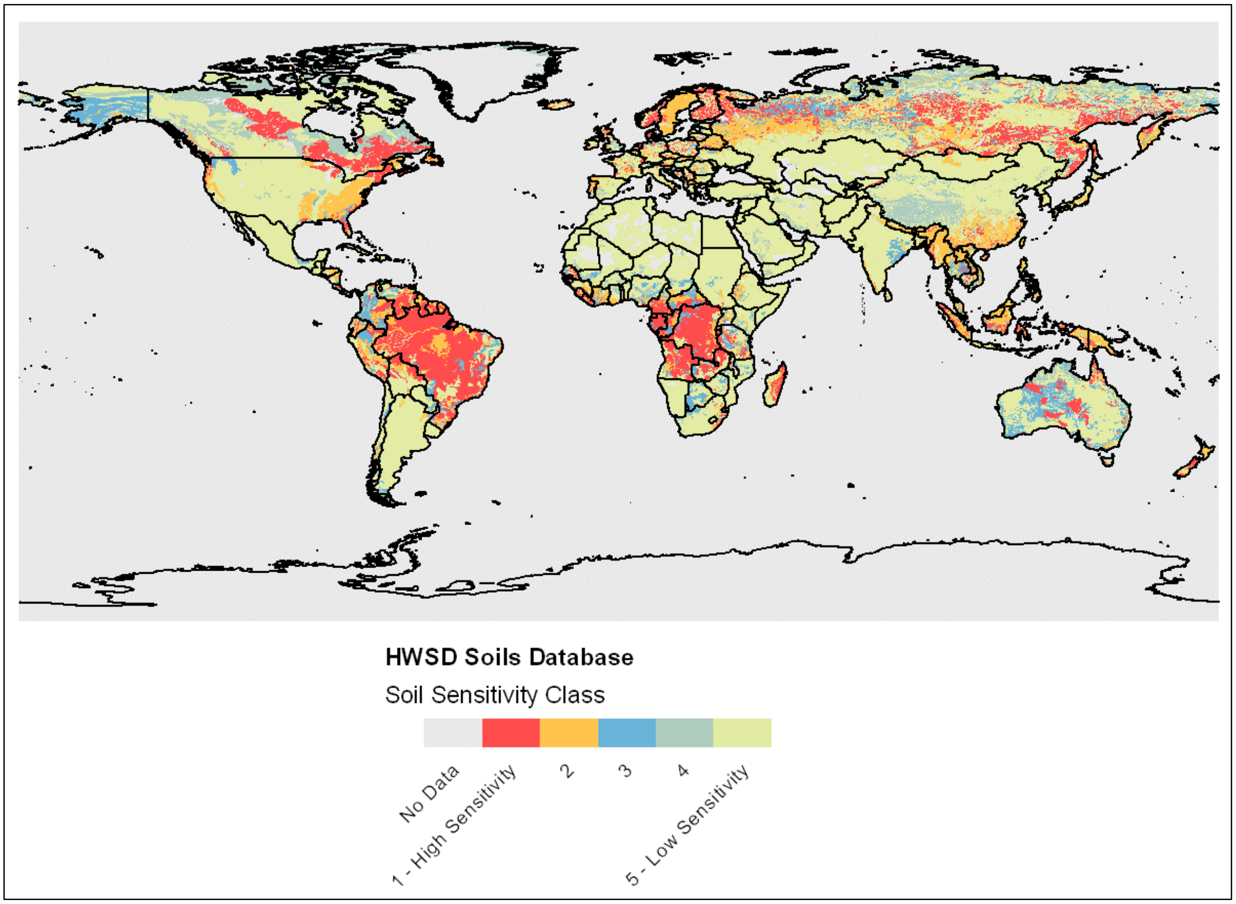

Figure F. 1. World distribution of acid soils

- ***Smog***

  Ground level ozone, a component of smog, is formed by the reaction of volatile organic compounds and nitrogen oxides in the presence of heat and sunlight. While ground-level ozone formation is complex, using a first-order assumption of a NOx-limited environment and reflecting global average conversion rates for NOx to ozone (Fry et al. 2012), the S-CF is one (1 tonne of O_3 per 1 tonne of NOx emitted).

  The World Health Organization (WHO) has defined a short-term air quality guideline as 100 µg/m^3 measured as the third highest 8-hour average over the course of the year. Ground level ozone is only considered when the ambient ozone concentration is above 100 µg/m^3 (otherwise M-CF equals zero). The M-CF is the average ozone concentration on days with concentrations above 100 µg/m^3, multiplied by the number of days over the threshold divided by the total measured days in the year or season, divided by 100 µg/m^3.

  Given that the ozone concentration in Muzaffarpur Collectorate, Muzaffarpur, India (used as proxy for all regions considered) was higher than the threshold for 10 days during the brick production season (December to May), and the average concentration in those days was estimated to be 135 µg/m^3, M-CF was calculated as 0.08.

Equation F. 2. M-CF calculation for smog impact category.

$$MCF = \frac{135\frac{\mu g}{m^3} \cdot \frac{10\ days}{178\ days}}{100\ \frac{\mu g}{m^3}} = 0.08$$

- ***Soot ($PM_{2.5}$)***

  Unlike ozone, exposure to particulate matter has impacts in human health at any concentration. Particles larger than 2.5 µm are not considered in this category; thus for those energy sources that have reported emissions of PM_{10} or unspecified, 90% of their weight was considered (S-CF). Regarding precursor emissions, SO_2 is also considered, and its S-CF is listed in Table F.4 below.[15]

Table F. 4. Soot S-CFs

Emission	*S-CF (ton $PM_{2.5}$ eq/ ton PM)*
PM_{10} and unspecified PM	0.9
SO_2*	0.36

**Emissions of all oxides of sulfur are characterized with S-CF for SO_2.*

Geographic characteristics were also considered, using the average annual air quality index[16] in Muzaffarpur Collectorate, Muzaffarpur, India (used as proxy). To ensure that the M-CF is a unitless quantity, the annual average was divided by 10 µg/m^3, the World Health Organization threshold. This allows for evaluation of the relative difference in the severity of impacts in different regions resulting from exposures to PM. The average concentration in the brick production season was estimated to be 164.6 µg/m^3, which yields an M-CF of 16.46.

Project Equation 3: M-CF calculation for Soot impact category.

$$MCF = \frac{164.6\frac{\mu g}{m^3}}{10\ \frac{\mu g}{m^3}} = 16.46$$

- ***Ocean Acidification***

  This impact category represents the degree to which emissions of CO_2 linked to brick production lead to decreases in the pH of the ocean through the formation of carbonic acid. Only CO_2 emissions are considered. Their S-CF (1.41 kg H_2CO_3 / kg CO_2) represents the kilograms of carbonic acid (H_2CO_3) formed per kilogram of emission. Around 25% of yearly CO_2 emissions are absorbed by the oceans (M-CF).[17]

- ***RF Inventory and Footprint Calculation***

[15] NOx is a soot precursor as well, however not enough data was found to include it in the calculation.
[16] https://aqicn.org/city/all/
[17] http://www.pmel.noaa.gov/co2/story/Ocean+Acidification.

A generic straight-line brick kiln's annual RF inventory and footprint and a zigzag brick kiln's RF inventory and footprint were calculated using data provided by the project developer and data found in the literature. This includes the RF resulting from CO_2, black carbon, and organic carbon emissions related to brick production in one year.

The annual RF inventory and footprint calculations were based on the amount of fuel the total energy used and the total bricks produced by the Brick Kiln. The radiative efficiency and lifetimes of all pollutants were taken directly from published literature (see Annex A), while for black carbon, the RE was derived (but not taken directly) from Bond et al., (2011), Table 1 for energy-related black carbon emissions in South Asia. Equation 4 was used for calculating the annual RF footprint.

Equation F.3. RF footprint calculation for Scopes 1 and 2

$$\text{Annual RF footprint} = \sum_{n=year\ 1}^{current\ year} \left(\sum_{j=substance} RF_n^j \times E_n^j + \sum_{i=Climate\ Forcers} RF_n^i \times E_n^i \right)$$

Where:

- RF_n are the radiative forcing factors of the different substances j (e.g., CO_2, methane, N_2O, black carbon, and SO_x) or climate forcers i that have a current, measurable effect on climate change, in year n. These factors include both the radiative efficiency and atmospheric lifetime by pollutant.
- E_n the emissions of the different substances j or climate forcers i in year n.
- $current\ year$ is the last 12-month period for which data are available

A sensitivity analysis considered that the snow and ice effects in this RE were 3x higher, accounting for the fact that most of these brick kilns are in northern India and so have a disproportionately higher impact. To sum them up, all numbers were transformed to CO_2fe by dividing each emission's RF by the radiative efficiency of CO_2.

F.4. Results

F.4.1 Summary of Results

Tables F.5 and F.6 provide a summary of how the RF Inventory for one brick kiln over 20 years, based on Scenario 1, is calculated in t CO_2fe and mW/m^2 respectively.

Table F. 5. RF Inventory calculation details for one brick kiln, based on Scenario 1. Units are tCO_2fe.

Calculation details for Years 4-19 are not shown.

Climate Forcers	*Year 1 (2022)*		*Year 2 (2023)*		*Year 3 (2024)*		*Year 20 (2041)*			*2050*	*2100*
	legacy	*current*	*legacy*	*current*	*legacy*	*current*	*legacy*	*current*	*total*	*total*	*total*
POSITIVE CLIMATE FORCERS											
Carbon dioxide (CO_2)	0	2,700	2,500	2,700	4,900	2,700	36,000	2,700	38,700	33,000	24,000
Nitrous Oxide (N_2O)	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Chlorofluorocarbons (CFCs)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hydrofluorocarbons (HFCs)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hydrochlorofluorocarbons (HCFCs)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Perfluorocarbons (PFCs)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Methane	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Black Carbon	0	94,000	0	94,000	0	94,000	0	94,000	94,000	0	0
Brown Carbon	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Mineral Dust Aerosols	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Decrease in albedo	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
NEGATIVE CLIMATE FORCERS											
Mineral dust aerosols	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Nitrate aerosols	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Organic carbon	0	-300	0	-300	0	-300	0	-300	-300	0	0
Sulfate aerosols	0	-31,000	0	-31,000	0	-31,000	0	-31,000	-31,000	0	0
Sea salt aerosols	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Increase in albedo	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

NC means Not Calculated: Data were not available to calculate potential CO_2fe from methane, N_2O, brown carbon, mineral dust aerosols and decreases in albedo. NA means Not Applicable. TO formation from VOCs not calculated.

Table F. 6. RF Inventory calculation details for one brick kiln, based on Scenario 1. Units are mW/m^2. Calculation details for Years 4-19 are not shown.

Climate Forcer	*Year 1 (2022)*		*Year 2 (2023)*		*Year 3 (2024)*		*Year 20 (2041)*			*2050*	*2100*
	legacy	*current*	*legacy*	*current*	*legacy*	*current*	*legacy*	*current*	*total*	*total*	*total*
POSITIVE CLIMATE FORCERS											
Carbon dioxide (CO_2)	0	4.7×10^{-6}	4.4×10^{-6}	4.7×10^{-6}	8.5×10^{-6}	4.7×10^{-6}	6.3×10^{-5}	4.7×10^{-6}	6.8×10^{-5}	5.8×10^{-5}	4.2×10^{-5}
Nitrous Oxide (N_2O)	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Chlorofluorocarbons (CFCs)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hydrofluorocarbons (HFCs)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hydrochlorofluorocarbons (HCFCs)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Perfluorocarbons (PFCs)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Methane	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Black Carbon	0	1.6×10^{-4}	0	1.6×10^{-4}	0	1.6×10^{-4}	0	1.6×10^{-4}	1.6×10^{-4}	0	0
Brown Carbon	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Mineral Dust Aerosols	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Decrease in albedo	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
NEGATIVE CLIMATE FORCERS											
Mineral dust aerosols	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Nitrate aerosols	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC
Organic carbon	0	-5.0×10^{-7}	0	-5.0×10^{-7}	0	-5.0×10^{-7}	0	-5.0×10^{-7}	-5.0×10^{-7}	0	0
Sulfate aerosols	0	-5.3×10^{-5}	0	-5.3×10^{-5}	0	-5.3×10^{-5}	0	-5.3×10^{-5}	-5.3×10^{-5}	0	0
Sea salt aerosols	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Increase in albedo	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Using this approach, the RF Inventories for all three scenarios for one brick kiln and scaled up to 40,000 brick kilns are summarized in Table F.7.

Table F. 7. RF Inventory Results for Brick Kiln 20-years after implementation (Scenarios 1, 2 and 3).
(NC stands for not calculated, NA stands for not applicable)

	1 kiln (tonnes CO_2fe)			*40,000 kilns (million tonnes CO_2fe)*		
Positive Climate Forcer [1)]	**S.1**	**S.2**	**S.3**	**S.1**	**S.2**	**S.3**
Carbon dioxide (CO_2)	39,000	26,000	5,500	1,500	1,000	220
Nitrous oxide (N_2O)	NC	NC	NC	NC	NC	NC
Chlorofluorocarbons (CFCs)	NA	NA	NA	NA	NA	NA
Hydrofluorocarbons (HFCs)	NA	NA	NA	NA	NA	NA
Hydrochlorofluorocarbons (HCFCs)	NA	NA	NA	NA	NA	NA
Perfluorocarbons (PFCs)	NA	NA	NA	NA	NA	NA
Methane	NC	NC	NC	NC	NC	NC
Black carbon	94,000	15,000	-5,500	3,600	730	-220
Brown carbon	NC	NC	NC	NC	NC	NC
Mineral dust aerosols	NC	NC	NC	NC	NC	NC
Decrease in Albedo	NC	NC	NC	NC	NC	NC
Waste Heat	NC	NC	NC	NC	NC	NC
Negative Climate Forcer	**S.1**	**S.2**	**S.3**	**S.1**	**S.2**	**S.3**
Mineral dust aerosols	NC	NC	NC	NC	NC	NC
Nitrate aerosols	NC	NC	NC	NC	NC	NC
Organic carbon	-300	-6.2	6,200	-11	-0.25	250
Sulfate aerosols	-31,000	-3,600	-3,200	-1,200	-140	-130
Sea salt aerosols	NA	NA	NA	NA	NA	NA
Increase in albedo	NA	NA	NA	NA	NA	NA

1) WMGHG results include all future (projected) residual levels integrated over the 20-year lifetime of the kiln.

The RF footprint and the LCA co-benefit/trade-off analysis in five additional impact categories results for one brick kiln are summarized in Table F.8 below by impact category.

Table F. 8. Study results for the three scenarios in Year One after retrofit of one brick kiln, including impact reduction percentages for Scenarios 2 and 3 compared to baseline Scenario 1

Indicator	*Unit*	*Scenario 1*	*Scenario 2*	*Scenario 2 %Reduction*	*Scenario 3*	*Scenario 3 %Reduction*
RF Footprint	kilotonnes CO_2fe	65	14	73%	-2.1	112%
Energy Resource Depletion	Terajoules (i.e., 10^{12} joules)	23	15	33%	Negligible	100%
Regional Acidification	tonnes	7.8	0.90	88%	0.79	90%
Smog	kilograms	70	47	33%	56	20%
Soot	tonnes	240	54	78%	-67	127%
Accumulated Ocean Acidification	tonnes	950	630	34%	130	86%

As can be seen in the table, the RF footprint and the change in soot in Scenario 3 are net negative. This is due to the elimination of burning of agricultural biomass, which more than offsets the positive RF from emissions from the retrofitted, pellet-fueled brick kiln, and reduces more soot than was emitted from the Scenario 1 kiln. Agricultural burning was not considered in the calculations of Scenario 1, since the straight-line kilns modeled here do not use biomass.

The avoided emissions, by pollutant, are shown in Table F.9.

Table F. 9. The emissions avoided each year in Scenarios 2 and 3, per kiln and per 40,000 kilns.

Avoided emissions per kiln (tonnes)					
	CO_2	BC	SO_2	Organic Carbon	PM
Scenario 2	900	1.5	6.9	0.098	10
Scenario 3	2300	1.9	7.0	2.2	18
Avoided emissions per 40,000 kilns (million tonnes)					
Scenario 2	36	0.060	0.28	0.0039	0.40
Scenario 3	92	0.076	0.28	0.088	0.73

Breaking down the RF inventory results (Figure F.2) in Year 1, the biggest contributor to the RF Footprint for both types of brick kiln is black carbon, representing 95% of the total positive RF in Scenario 1, and 85% in Scenario 2. Scenario 3 black carbon has a negative value because avoided black carbon emissions are higher than the emissions generated. Similarly, Scenario 3 organic carbon has a positive value because avoided organic carbon emissions are higher than the emissions generated. From a net RF standpoint, the significant drop in organic carbon and SOx emissions associated with Scenarios 2 and 3 does reduce the overall RF benefit to some degree, but in the case of SOx, it also has important co-benefits in terms of significantly improved regional air quality, accounted for both in terms of reduced acidification and contribution to soot in Table F.8.

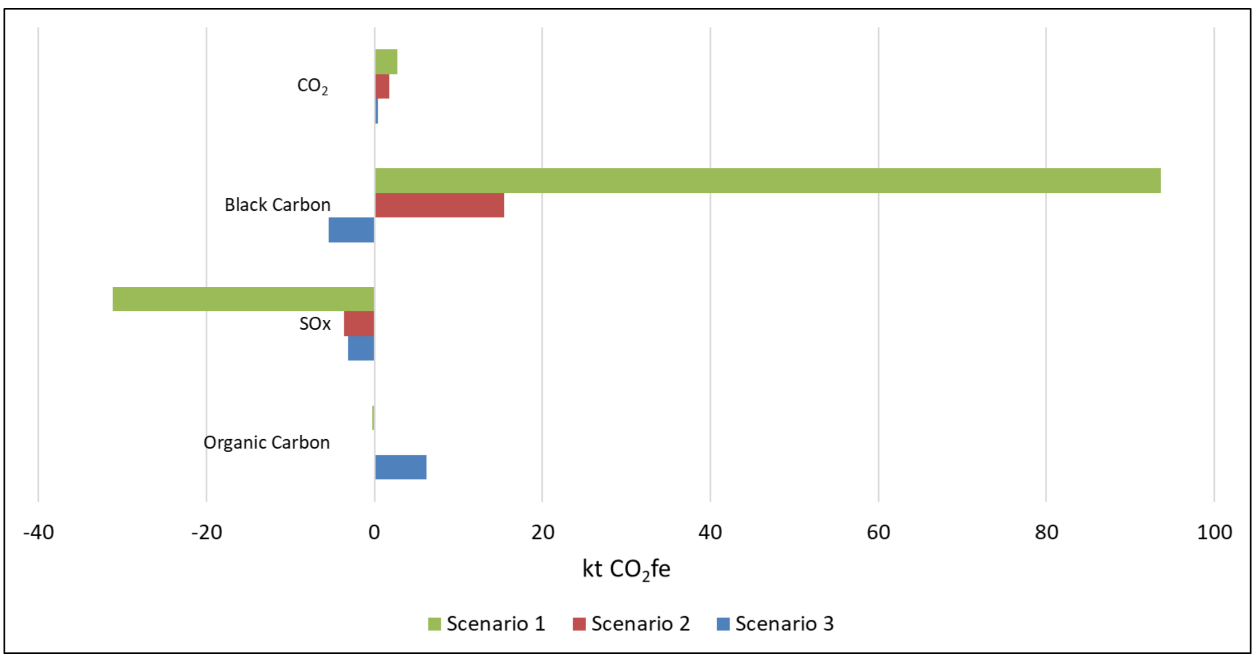

Figure F. 2. The kt CO_2fe in year 1 for three scenarios compared by emission

F.4.2 RF Over Time

The chart below (Figure F.3) shows how the RF reduction benefit changes over time for the brick kiln retrofits.

- Black carbon reduction is the most important vector of RF reduction for the 20-year lifetime of the kiln, remaining constant over the lifetime of the kiln, but not increasing each year since this is a very short-lived pollutant.
- The CO_2 RF reduction does increase over time, although this accumulation never reaches the RF reduction from black carbon. The modeling is calculated based upon emissions reductions beginning in 2020 and being maintained at full scale for 20 years, a reasonable lifetime for the brick kiln. Beyond that timeframe, it is highly uncertain to project whether the kiln will keep operating. Beyond this timeframe, the continuing legacy RF reduction for CO_2 emissions after Year 20 is calculated, without including any further emissions.

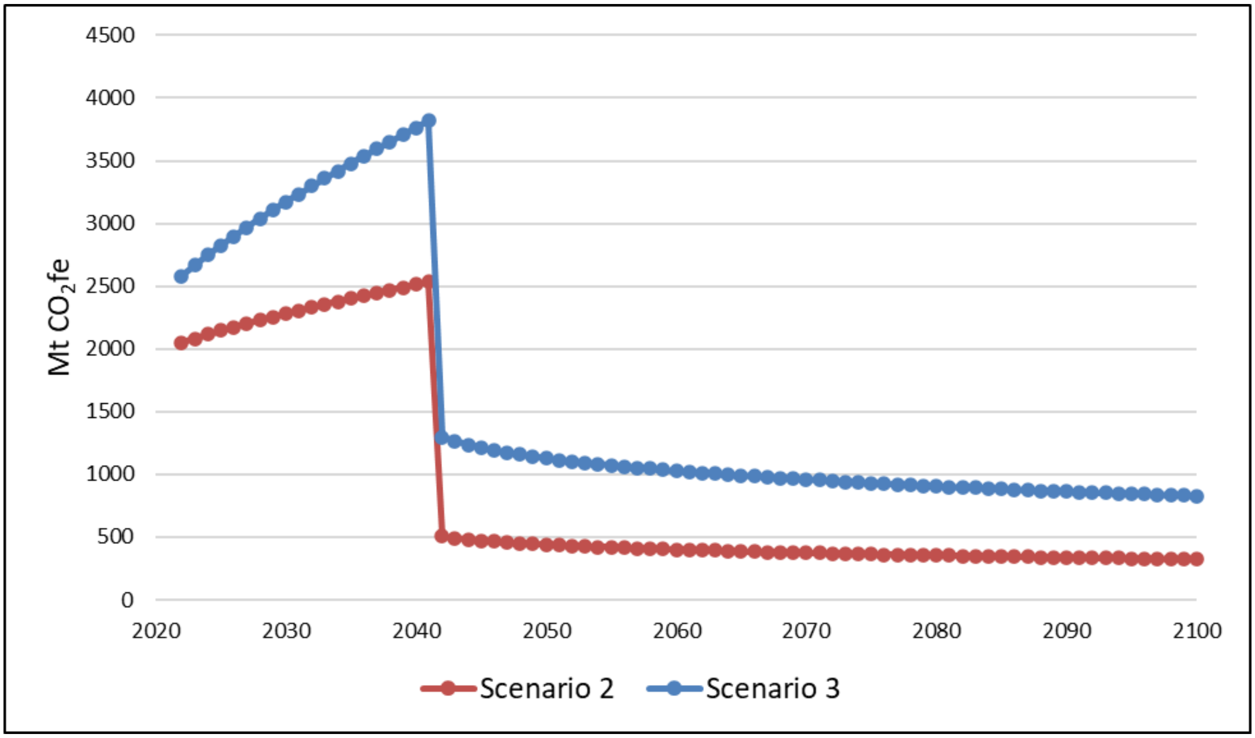

Figure F. 3. Net RF reductions for Scenarios 2 and 3 for 40,000 brick kilns, assuming 2022 as the year of implementation and a kiln lifetime of 20 years

The RF slope is reduced in Scenarios 2 and 3 as black carbon and CO_2 emissions are reduced, as well as SO_2. In Scenario 3, there is net negative RF during the first 7 years of kiln operation due to the transition of agricultural wastes that are normally burned in the field into pellets for use as fuel for the kilns.

The total climate benefits are shown for the retrofit of 40,000 kilns over three different time horizons (2030, 2050, and 2100) in Table F.10, and for the retrofit of 40,000 kilns over a 20-year lifetime, assuming that retrofits take place in 2022, in Table F.11.

Table F. 10. RF reductions for Scenarios 2 and 3, compared to the baseline Scenario 1, for 40,000 kilns compared to the baseline Scenario 1over three different time horizons (2030, 2050, and 2100)[1)]
All values calculated in gigatonnes (billion metric tons) and rounded.

		Scenario 2 – Net Reduction (40,000 kilns)			Scenario 3 – Net Reduction (40,000 kilns)		
Indicator	Unit	2030	2050	2100	2030	2050	2100
CO_2	Gt CO_2fe	0.27	0.44	0.32	0.68	1.1	0.83
Black Carbon	Gt CO_2fe	3.1	0	0	3.7	0	0
Organic Carbon	Gt CO_2fe	-0.011	0	0	-0.012	0	0
SOx effects on sulfate aerosols	Gt CO_2fe	-1.1	0	0	-1.2	0	0
Positive RF reduction	Gt CO_2fe	3.4	0.44	0.32	4.4	1.1	0.83
Negative RF reduction	Gt CO_2fe	-1.1	0	0	-1.2	0	0
Net Total RF reduction [2)]	Gt CO_2fe	2.3	0.44	0.32	3.2	1.1	0.83
Total RF Footprint	Gt CO_2fe	2.3	0.44	0.32	3.2	1.1	0.83

[1)] Because sulfate aerosols from SOx emissions and organic carbon both exert a negative RF influence, reductions in these indicator categories result in increasing positive RF, shown in Tables F.8 and F.9 as negative numbers.

[2)] Net total RF reduction is not always identical to RF footprint, since only positive forcers and decreasing levels of negative forcers are included in the RF footprint (see discussion, Section V.4 above). However, in this case they are the same due to rounding.

Table F. 11. RF reductions for Scenarios 2 and 3 at Year 20 (2042)
for 40,000 kilns compared to the baseline Scenario 1
All values are calculated in gigatonnes (billion metric tons) and rounded to two significant digits.

Indicator	Unit	Scenario 2 Year 20 reduction (40,000 kilns)	Scenario 2 Year 20 accumulated reduction (40,000 kilns)	Scenario 3 Year 20 reduction (40,000 kilns)	Scenario 3 Year 20 accumulated reduction (40,000 kilns)
CO_2	Gt CO_2fe	0.52	5.9	1.3	15
Black Carbon	Gt CO_2fe	3.1	63	3.7	75
Organic Carbon	Gt CO_2fe	-0.011	-0.23	-0.011	-0.24
SOx effects on sulfate aerosols	Gt CO_2fe	-1.1	-22	-1.2	-25
Positive RF reduction	Gt CO_2fe	3.6	69	5.0	90
Negative RF reduction	Gt CO_2fe	-1.1	-22	-1.2	-25
Net Total RF reduction	Gt CO_2fe	2.5	47	3.8	65

F.4.3 Key Limitations and Assumptions

The following assumptions are important to understand, as some result in study limitations. The assumptions with the most important effects on final results are as follows:

- *Emissions from previous studies for Scenarios 1 and 2:* ICIMOD was not aware of any before-and-after studies conducted on brick kilns converted from straight-line to zigzag technology. Thus, the emission factors used are based on comparison of the two types of kilns; however, some characteristic brick kiln parameters might vary (e.g., brick weight, fuel mix used, number of bricks produced per year).

NOTE: After completion of this case study, Pakistan's Ministry for Climate Change has reported a set of emissions reduction values for CO_2, PM and BC based on conversion of 11,000 brick kilns, with emission reductions reported at 15%, 40%, and 60% respectively (Jamshaid, S.H., 2022).

- *Use of fuel pellets made from rice husks in Scenario 3:* It is not clear that rice husks can realistically be collected from fields for pelletization and use. Scenario 3 assumes a sufficient feedstock of such pellets could be established to power these kilns.
- *Pellet emissions for Scenario 3:* No data for pellet-fueled brick kilns were found. Emissions from wood pellet stoves were used as proxy.
- *Soot and ozone:* The World Air Quality Index project does not have data for the target region in Nepal, so to calculate the M-CFs for soot and ozone, Muzaffarpur Collectorate, Muzaffarpur, India was used as proxy based on its similar geographic characteristics.
- *Emissions avoided for Scenario 3:* Data were taken from open burning paddy stalk as a proxy of rice husk.
- *CO_2 emissions from biomass*: The burning of biomass (open burning and pellets) was considered CO_2 neutral.
- *Caloric capacity of pellets for Scenario 3:* The project developer recommended that pellets be assumed to have a caloric capacity similar to coal.
- *Uncertainty about scaling to 40,000 kilns.* It is unclear to what extent these estimates, based upon literature estimates and characterized for single regions, would extend across all of India or south Asia.
- *Uncertainty about availability of biomass for pellets used in Scenario 3.* It is unclear if there is sufficient capacity to produce enough biomass pellets from waste biomass which would have been burnt in the open to power 40,000 kilns. An economic and technical assessment of the logistics and costs of collecting this crop residue from the field was not completed.

F.5 Analysis and Conclusions

As the results above demonstrate, impacts from all categories were significantly reduced across the board through brick kiln retrofit conversion to either Scenario 2 or Scenario 3, assuming that the plant production levels remain the same. Use of biomass pellets generated from rice husk as fuel resulted in the greatest RF reduction and co-benefits (energy resource depletion, soot, accumulated ocean acidification). Scenarios 2 and 3 offered comparable benefits for regional acidification reduction (88-90%), while for smog reduction, Scenario 2 showed 33% reduction and Scenario 3 showed 20% reduction.

For Scenario 3, the greatest reduction was of soot, with 127% reduction over Scenario 1. This is explained by the avoided emissions from open burning of rice husk (paddy stalk was used as proxy). The second biggest reduction for Scenario 3 is in the RF reduction with 112%, also explained by the reduced black carbon emissions from avoiding the open burning of rice husks.

The smallest reductions for Scenario 2 were energy resource depletion and accumulated ocean acidification at 33% each. The smallest reductions for Scenario 3 were smog at 20%, and regional acidification and accumulated ocean acidification at 90% and 86% respectively.

To improve the quality and precision of results, it would be recommended that data be used from one or several kilns that were converted from straight-line to zigzag, before and after the conversion, and data from brick kilns fueled with rice husk pellets. This approach would ensure that all characteristic brick kiln parameters and the emission measurement method under comparison remain constant.

Extrapolating from these results, the retrofit of 40,000 kilns in India under Scenario 2 would be projected to result in the accumulated net reduction of ~42 billion metric tons CO_2fe over 20 years. The total PM and black carbon emissions reduction each year from retrofitting 40,000 kilns are projected at 0.4 and 0.06 million tons; this means such a project could reduce overall PM and black carbon emissions in India by 7% and 8%, respectively (Ganguly et al., 2021; Paliwal et al., 2016).

F.6 Comparing RF Protocol and GWP-based accounting for brick kiln example

Figure F.4 demonstrates the difference in accounting between CO_2fe of the RF Protocol and CO_2e from GWP-based accounting (GWP-100). CO_2e is based on GWP-100 values, and only includes emissions of CO_2, as it is the only WMGHG included in the project calculation. Emissions of CO_2 avoided per year is constant, leading to the same value of CO_2e each year. As discussed previously, CO_2fe includes non-well-mixed climate forcers as well as WMGHG and increases over time due to the accumulation of legacy GHG emissions.

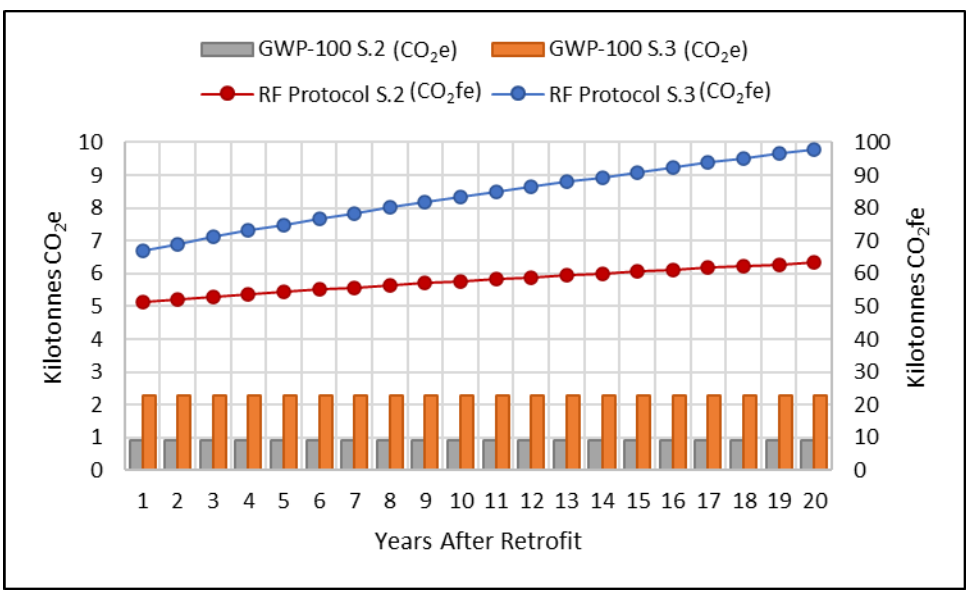

Figure F. 4. Comparison of CO_2e and CO_2fe emissions avoided in Scenario 2 and 3 for a single kiln over 20 years

Table F. 12. Comparison of GWP-100 and RF Protocol avoided equivalent tonnes of CO_2 over 20 years in Scenarios 2 and 3, per kiln and per 40,000 kilns.

	GWP-100 (t CO_2e)	*RF Protocol (t CO_2fe)*
Per kiln		
Scenario 2	18,000	1.6 million
Scenario 3	46,000	2.3 million
Per 40,000 kilns		
Scenario 2	36 million	3.0 billion
Scenario 3	92 million	3.9 billion

As described earlier, the RF Protocol accounts more fully for the climate forcing from an industrial system, and is particularly well suited to demonstrating benefits from reducing emissions of SLCFs and the long-term benefits of reducing long-lived WMGHGs.

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